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URMAS RUNOLINNA

Dry Magnetic Separation of Finely Ground Magnetite in a Rotating Magnetic Field

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DRY MAGNETIC SEPARATION OF FINELY GROUND MAGNETITE IN A ROTATING MAGNETIC FIELD

by

URMAS RUNOLINNA

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PREFACE

All the experimental work reported in this paper was carried out during the period 1956-1960 in the mineral dressing laboratory of Otanmäki Oy.

The subject of this investigation was suggested by Professors R.T.HUKKI and ERKKI LAURILA of the Institute of Technology. It is a great pleasure to express my thanks to both of them for their active interest, help and guidance.

The co-operation of Messrs R.RINNE, S.KURRONEN and M.HEIKKINEN of the Otanmäki concentrator is gratefully acknowledged.

I also wish to record my appreciation of the assistance rendered by Major J.MERIÖ and Captain J.PUKKILA, Research Centre of the Finnish Army, who took the high speed motion pictures.

This work was made possible by Otanmäki Oy, which defrayed the costs of all the investigations. My thanks are due to the company, its General Manager, Mr. I.HARKI, and the Technical Manager, Professor K.JÄRVINEN.

I also acknowledge with pleasure the financial support granted me from the Finnish Academy of Technical Sciences.

Finally I am happy to have the opportunity of expressing my thanks to Miss ANNE ALEXANDER and Mr. FRED A.FEWSTER for correcting the English text of the manuscript.

Otanmäki, 15 December 1960.

URMAS RUNOLINNA

CONTENTS

LIST OF SYMBOLS

(Some of the symbols used only once and explained in the context are omitted from the list.)

a = half of the long axis of an ovoid of magnetite powder

b = half of the short axis of an ovoid of magnetite powder

B = magnitude of magnetic induction in a stringer of magnetite

B_o = (total) flux density on drum surface

c = volume concentration of magnetite powder

C = constant

d = thickness of separator drum

f = frequency of a rotating magnetic field observed at a point on the surface of drum

F_c = centrifugal force

F_m = magnetic attractive force

F_p = $F_m - F_{c_1}$, resultant attractive force

H = magnitude of magnetic field

H_o = magnitude of magnetic field on drum surface

H_x = tangential component of magnetic field

H_y = radial component of magnetic field

m = mass of a magnetite stringer

n = constant

n = number of revolutions of drum in a given time

n_c = critical number of revolutions of drum

N = demagnetizing factor

r = radius of drum

s = bulk density of a magnetite stringer

t = time

U = magnetic potential energy

v = peripheral velocity of drum

v_s = linear velocity of magnetite stringer

V = volume of the magnetite powder (or stringer)
x = tangential distance from an arbitrary origin
y = radial distance outwards from the surface of drum

λ = distance between similar poles
μ_a = effective magnetic permeability of a magnetite particle or magnetite powder
μ_o = permeability in vacuum = $4 \times 10^{-7}\ \frac{V s}{A m}$
σ = "tensile" strength of a magnetite stringer caused by magnetic induction
φ = rotation angle of a magnetite stringer
ω_o = relative angular velocity of the magnet system against the outer drum
ω = angular frequency of the magnetic field observed at a point on the surface of drum
ω_r = angular velocity of drum

INTRODUCTION

1. Scope of the present work

In magnetic separation, the magnetic attraction force created by an inhomogeneous magnetic field holds the magnetic particles in the field, while other forces, such as the force of gravity, water rinsing, air blowing, and/or centrifugal force, are used to escape the non-magnetic particles.

Present-day dry magnetic separators have a rotating magnetic field whose aim is to break up the groups of magnetite grains, and thus release from them locked non-magnetic particles.

The use of a rotating magnetic field in separators is, as such, no new idea. A Swedish patent for such a separator was taken out in 1895 [1]. Taggart's handbook[2] contains a description of a separator based on this system although its magnet wheel rotates in the reverse direction.

Earlier separators had a rotating magnetic field created by alternating electric current[3-7]. Such separators have the disadvantage of weak field strength. There is not sufficient room within the drums for coils with the requisite number of ampere winding turns. For the same reason, D.C. magnets producing a sufficiently strong field would require so much space that the pole distance would be considerable and thus the field frequency low[8]. Not until recently have the permanent magnets developed in the last decades made it possible to produce strong magnetic fields with a pole distance of only a few centimetres [9-12].

The best form for a dry separator is that of a rotating drum, as it is then possible to use centrifugal force to discharge non-magnetic particles. The drum can have peripheral speed of such magnitude that only the strongly magnetic grains remain on its surface, gangue and/or middling particles flying away.

LAURILA has described the construction of such a drum separator[13] and made a theoretical study of the phenomena of dry separation in a rotating field[14]. These theories for dry separation have been formulated with the assistance of some greatly simplified theoretical models. It was thus desirable to make an experimental examination of the effects of the different variables in dry separation.

The main part of this work consists of an examination of the effect of the rotating magnetic field. Other variables, such as magnetic attractive and centrifugal force, and the nature of the magnetite materials, have also been investigated, as all the variables combine to exert an influence on the separation.

The ultimate aim of the work was that of arriving at some conclusion regarding optimum conditions for dry separation of finely ground magnetite.

TEST PROCEDURE AND EQUIPMENT

2. Magnetite materials

Four magnetite ores from Northern Finland and their respective magnetite concentrates were used as test materials. Artifical mixtures of pure magnetite and some nonmagnetic mineral might have been easier to analyze. However, such mixtures were not used because they are too easy to separate, and some phenomena exerting an important effect on separation could have been overlooked[15]. These phenomena include the dust of gangue minerals, which during the grinding adheres to the surface of magnetite grains, and the behaviour of half grains; ground samples of natural ores always contain a proportion of half grains.

The mineral composition of the ores is given in Table 1:

Otanmäki ore is a magnetite-ilmenite ore with a fairly good selective crystallization. However Otanmäki magnetite always contains finely disseminated inclusions of ilmenite. Thus even the fine grain sizes assay only 70.0 % Fe, c.f. Table 2. In addition, about 10 % of the ilmenite in the ore carries veinlets of magnetite, which make ilmenite somewhat magnetic. The size of magnetite crystals varies from 0.1 mm to 1.0 mm, but is in the main 0.2 mm.

Porkonen ore is a very finely grained magnetite ore of the taconitic type. The size of the magnetite crystals is about 0.02 mm. They contain very small inclusions of quartz and the contact lines of the magnetite and quartz crystals are uneven. Not even fine grinding liberates the magnetite from quartz, and thus the magnetite contains only 68.4 % Fe.

Kärväsvaara ore is a rich magnetite ore of magmatic type. The magnetite crystals are well-formed with an even grain size of 0.2-0.3 mm. The grains are weakly attached to each other. The ore is easy to grind, and the magnetite concentrate is of high grade even with relatively coarse grinding.

Raajärvi ore is also a relatively rich magmatic magnetite ore. The magnetite crystals are not so well formed as in Kärväsvaara. The size of the crystals is nearly the same as in Otanmäki. The magnetite grains contain inclusions of silicates, and thus their Fe-grade is only 70.7 %.

Table 1.

Average mineral composition of Otanmäki, Kärväsvaara, Porkonen and Raajärvi ores.

	OTANMÄKI	KÄRVÄSVAARA	PORKONEN	RAAJÄRVI
	Wt. per cent	Wt. per cent	Wt. per cent	Wt. per cent
Magnetite	30	76	32	64
Hematite	-	1	4	2
Ilmenite	27	-	-	-
Pyrite	1,5	2	-	-
Apatite	0,2	0,2	-	1
Feldspar	7	-	4	-
Amphiboles	20	-	5	-
Chlorite	14	-	-	10
Epidote	-	21	-	-
Serpentine	-	-	-	20
Dolomite	-	-	-	3
Quartz	-	-	53	-
Others	-	-	2	-

Table 2.

Chemical analyses of two samples, of different grain size of specially cleaned magnetite from Otanmäki, Kärväsvaara, Porkonen and Raajärvi ores.

	OTANMÄKI		KÄRVÄSVAARA		PORKONEN		RAAJÄRVI	
	100-400 mesh	Pulverized sample	100-400 mesh	Pulverized sample	100-400 mesh	Pulverized sample	100-400 mesh	Pulverized sample
Fe, per cent	69,6	70,0	71,5	72,0	66,9	68,4	70,0	70,7
Fe_{II} -"-		24,1		23,4		16,5		20,7
Fe_2O_3 -"-		65,6		69,5		67,8		71,5
FeO -"-		31,0		30,1		21,0		26,6
V_2O_3 -"-	0,92	0,93		0,09				0,1
TiO_2 -"-	0,85	1,10		-	traces	traces		0,05
SiO_2 -"-	0,72	0,66		0,25	8,06	4,95		0,22
S -"-	0,10	0,08		0,03		traces		0,02

The necessary fineness of grinding for magnetite liberation can be determined from the values in Table 3. It presents the Fe-grade of different grain sizes of dry concentrated magnetite concentrates. Satisfactory Fe-grades are obtained with grain sizes of <0.5 mm of Kärväsvaara ore, <0.2 mm of Otanmäki and Raajärvi ores, and <0.05 mm of Porkonen ore.

Table 3.

Fe-grade of different grain sizes of dry separated magnetite concentrates of Otanmäki, Kärväsvaara, Porkonen and Raajärvi ores.

Grain size		OTANMÄKI	KÄRVÄSVAARA	PORKONEN	RAAJÄRVI
Tyler mesh	Microns	Fe, per cent	Fe, per cent	Fe, per cent	Fe, per cent
28/48	590/294	-	67,2	-	-
48/70	294/209	51,9	69,1	-	56,3
70/100	290/146	65,7	71,2	-	65,8
100/150	146/105	66,7	71,4	58,3	67,8
150/200	105/74	68,5	71,5	57,8	68,2
200/270	74/54	67,8	71,5	57,3	68,7
270/400	54/37	66,0	71,4	62,9	69,2
-400	- 37	-	70,8	66,9	-

Table 4.

Screen analyses, values of surface measurements, and magnetite content of the ore samples used in the separation tests.

Grain size		OTANMÄKI Fineness A	OTANMÄKI Fineness B	OTANMÄKI Fineness C	KÄRVÄSVAARA	PORKONEN	RAAJÄRVI
Tyler mesh	Microns	Cum. %	Cum. %	Cum. %	Cum. %	Cum. %	Cum. %
100	146	92	99	-	80	-	93
200	74	50	70	90	40	99	50
400	37	25	35	45	20	65	25
Surface cm^2/cm^3		5250	7500	13900	4290	18000	6400
Fe_3O_4, per cent		24-31	24-31	24-31	56,0	42,5	61.5

The ores were crushed to a fineness of 1.5 mm and divided into 5 kg samples. These samples were ground in a 190 ∅ x 230 mm laboratory ball mill for a definite period to obtain the desired grinding fineness.

The fineness of the ground samples was determined by screening in Ro-Tap apparatus with Tyler standard sieves, and by surface measurements in accordance with the gas permeability method devised by SVENSSON[16]. The average values are given in Table 4.

In order to get sub-sieve size fractions, the minus 400 mesh magnetite of Kärväsvaara was classified by the sedimentation-decantation method. Microscopic investigation of the products showed that the classification had not been successful. The material was magnetically flocculated. Efforts to demagnetize the material with a coil using an alternating current of 50 cycles failed. The minus 400 mesh magnetite had to be changed first into hematite, this hematite was classified, then the classified products were changed back into magnetite. The oxidizing roasting

was carried out at a temperature of 800° C for five hours. The hematite was slightly sintered, and was therefore ground before classification. The classified products were reduced in a hydrogen atmosphere at 300°C for one and a half hours, and cooled to room temperature; they were kept all the time in the hydrogen atmosphere. Microscopic investigation showed that the classified products so obtained had an even grain size. The susceptibility of this material was 10 per cent stronger than the susceptibility of the original magnetite measured by means of a magnetite analyser.

The magnetite analyzer employed in the above mentioned investigations was developed in Otanmäki from a drill core analyzer[17]. It contains a primary coil which produces a magnetic field. When a given amount of magnetic powder, packed in a small plastic container, is introduced into the magnetic field, it causes a change in the flux of the field, and results in a change in the voltage difference of secondary coils. This voltage difference can be read off on a micro ammeter, and the reading is a function of the combined susceptibilities of all magnetic grains in the magnetic field.

Unfortunately the reading also depends on the fineness and on the packing density of the magnetite powder. The relative accuracy of this analyzer is accordingly only about $\pm$ 1 %.

The magnetite content of the products obtained in most of the separation tests was analyzed by the magnetite analyzer. The Fe_3O_4-values in Tables 16 and 17 and Fig. 27 were checked by chemical methods.

3. Separators

Tests were carried out with two types of separators. In the paragraphs which follow they are termed separators Nos. 1 and 2.

Separator No. 1 is of the so-termed Laurila type, c.f. Fig. 1 A, with a drum diameter of 1000 mm, width 100 mm and pole distance 52 mm. The shell is made of 2 mm thick polyvinylcloride plate.

Separator No. 2 is of the Mörtsell-Sala type, c.f. Fig. 1 B, with a drum diameter of 400 mm, width 100 mm and pole distance 35 mm. The shell is made of 1.2 mm thick austenitic steel.

The field strength of the two separators was measured by means of an instrument based on the Hall effect. The resuts are given in Fig. 2.

Over a hundred tests were made with separator No. 1 in order to study the performance of two types of induction rollers: a) a roller made of brush sheaves with 0.5 mm steel bristles, b) a roller made alternately of 1 mm thick steel plates and 4 mm thick plastic plates (of 85 mm diameter), the rim of the steel plates being saw-toothed with 5 mm teeth having an edge distance of 5.2 mm.

The following conclusions could be drawn from the tests:

- The brush and plate type induction rollers function in a similar fashion.
- The induction roller does not remove the magnetite if the speed of the roller is less than 200 r.p.m. Above this rate, a further increase in the number of revolutions has no effect on separation results.

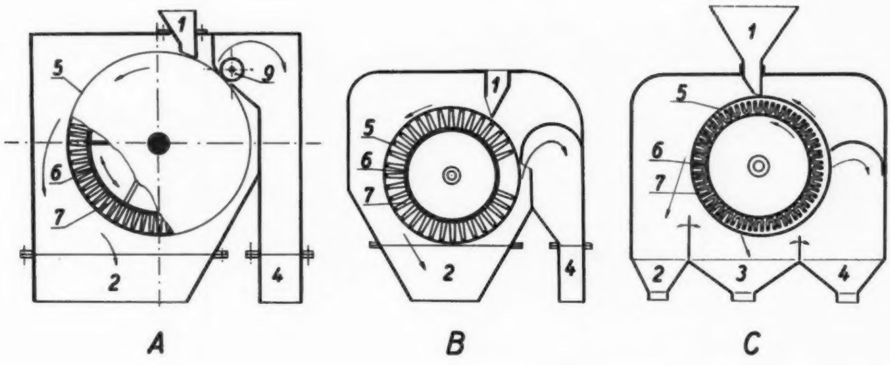


Fig. 1. Dry separators with a rotating magnetic field. A) Laurila separator, B) Mörtsell-Sala separator, C) Cavanagh separator
1- introduction of feed, 2-discharge of tailing, 3- discharge of middling, 4-discharge of concentrate, 5- drum, 6- magnet carrying wheel, 7- permanent magnet, 9- induction roller.

- These two conclusions hold good at different drum speeds, different magnet wheel speeds and directions, and with different feed rates.

In the separation tests described in what follows, an induction roller made of brush sheaves rotating at 1500 r.p.m. was employed.

4. Photographic equipment

The behavior of magnetite particles in a rotating field was photographed with a standard and a high-speed motion camera.

The standard camera was a Contaflex III, with a Carl Zeiss Proxar f = 0.2 m close-up attachment. The photographs were taken at a distance of 0.2 m. The camera was synchronized with Microflash equipment, flash duration 2×10^{-6} seconds, situated at a distance of 0.3 m from the object. In order to eliminate diffused light the exposure time of the camera was 1/500 s. The lens aperture was set at f. 8 and the film was Agfa Isopan Record.

The high-speed motion camera pictures were taken with a Fastax WF3 by experts of the Research Centre of the Finnish Army, on Pathe Tri-X films. The camera has the following characteristics:

- Film capacity 100 feet.
- Aperture plate 16 mm.
- Filming rate from 150 to 8000 pictures per second.

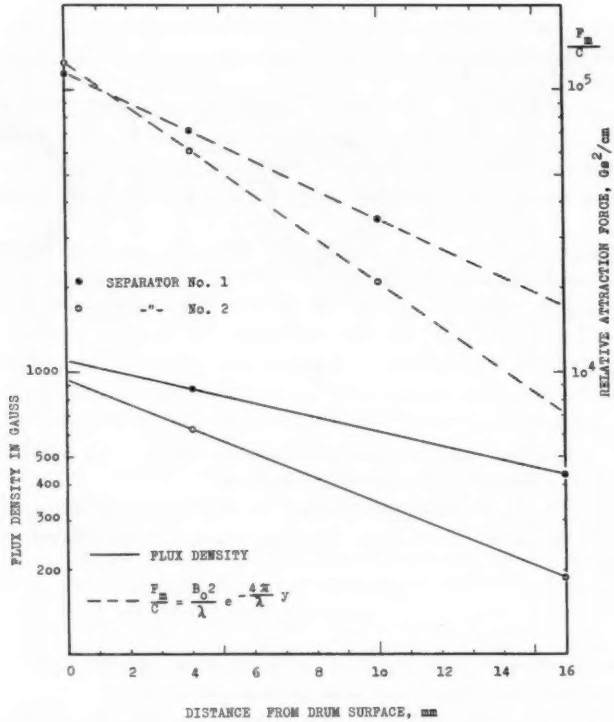


Fig. 2. Change of measured flux density and the quantity F_m/C, relative to magnetic attractive force, as a function of distance from the drum surface of separators Nos. 1 and 2.

The photographic conditions were difficult because of dust and lack of space. There was no opportunity to make a previous check of the correct exposure times. Although a number of the films were unsatisfactory, others were sufficiently clear to permit of verification of the behaviour of magnetite in a rotating field.

THE BEHAVIOUR OF MAGNETITE POWDER IN A ROTATING MAGNETIC FIELD

5. Theoretical study

LAURILA attempted in his separator construction to establish a rotating magnetic field which was homogeneous and strong enough on the surface of the drum, but which decreased with the increase in the distance in a radial direction from the drum surface. If the surface of the drum is considered as an xz-plane, and the magnet poles have the direction of the y-axis, c.f. Fig.3, the field may be approximately described by the function[14, 18]

(1)
(6.1/14)*)

$$\begin{cases} H_x = H_o e^{\frac{-2\pi}{\lambda} y} \cos \frac{2\pi r}{\lambda} \omega_o \left(t - \frac{x}{\omega_o r} \right) \\ H_y = H_o e^{\frac{-2\pi}{\lambda} y} \sin \frac{2\pi r}{\lambda} \omega_o \left(t - \frac{x}{\omega_o r} \right). \end{cases}$$

At a given point (x, y) the field vector H, with a constant value, rotates in a direction opposite to that of the magnet wheel. The direction of rotation of the magnet wheel is here relative to that of the drum and must be observed at a point on the surface of the drum. The functions of angular frequency and frequency of the rotating magnetic field are

(2)
$$\omega = \frac{2\pi r}{\lambda} \omega_o ,$$

and

(3)
$$f = \frac{\omega}{2\pi} = \frac{r}{\lambda} \omega_o .$$

*) Indicates the number of the formula, 6.1, in reference 14.

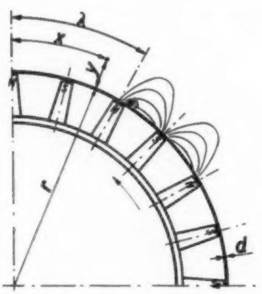


Fig. 3. Diagrammatic drawing of a rotating field on the drum of a Laurila-type separator.

The magnitude of the magnetic field (1), $H = H_0 e^{\frac{-2\pi}{\lambda} y}$, is independent of x and t. When a magnetite particle or a group of magnetite particles is introduced into such a field they are influenced by a magnetic attractive force, which is also independent of x. The formula of the attractive force is

$$(4) \qquad F_m = \frac{(\mu_a - 1)\mu_o}{1 + N(\mu_a - 1)} VH \frac{dH}{dy} = \frac{(\mu_a - 1)\mu_o}{1 + N(\mu_a - 1)} V \frac{2\pi}{\lambda} H_0^2 e^{-\frac{4\pi}{\lambda} y},$$

where μ_a is the effective permeability and V the volume of the magnetic particle or the magnetite powder, and N the demagnetizing factor of the volume V.

The magnetic potential energy of the system (4) is

$$\begin{matrix}(5)\\(4.1/14)\end{matrix} \qquad U = -\frac{1}{2} \frac{(\mu_a - 1)\mu_o}{1 + N(\mu_a - 1)} VH^2 .$$

The effective magnetic permeability μ_a depends on the packing and purity of the magnetite powder. Laurila derived an approximate function for this

$$\begin{matrix}(6)\\(3.2/14)\end{matrix} \qquad \mu_a = 1 + 3c + 9c^2 + \dots\dots\dots ,$$

where c is the volume concentration of the magnetite powder.

If we assume that a certain large number of particles fills volume V, we get

$$(7) \qquad cV = \text{constant} = n .$$

Function (5) can now be written in the form

(8)
(4.1/14)

$$U = -\frac{3}{2} n \frac{1 + 3c}{1 + N (3c + 9c^2 + \dots)} \mu_o H^2 ,$$

Magnetite powder in a magnetic field attempts to take up such a position that the potential energy of the system is as small as possible. In view of the fact that field strength H changes but little and demagnetizing factor N always has a value under one [14], the potential energy attains its minimum value when concentration c is at its peak. Under these circumstances, magnetite powder will be drawn into the more intensive parts of the field, and form a number of elongated stringers in the direction of the field lines.

The magnetite stringer has comparatively great strength, with an approximate value of

(9)
(5.1/14)

$$\sigma = \frac{1}{2} \mu_o H^2 \left(\frac{\mu_a^2}{[1 + N(\mu_a - 1)]^2} - 1 \right) .$$

This function provides verification that as long as saturation is not reached, the "tensile" strength of magnetite stringer rises with increasing field strength and effective permeability. The form and strength of a magnetite stringer is also dependent on other factors such as the homogeneity of the field, the grain size distribution of magnetite powder, the shape of individual particles, the adhesion forces between the grains, the amount of non-magnetic material in the magnetite powder, etc.

In addition to the magnetic attraction force (4), which presses the stringers against the drum surface and is caused by the inhomogeneity of the magnetic field, the rotating field causes a torsional moment which makes the stringers rotate along the surface.

If the drum is rotating at an angular velocity ω_r and this velocity is much less than the angular frequency of the magnetic field, $\omega_r \ll \omega$, and the long axis of a magnetite stringer of mass m is much shorter than the diameter of the drum, $2a \ll 2r$, then the centrifugal force acting on the stringer can be divided into two parts:

(10)
(9.3/14)

$$F_c = F_{c_1} - F_{o_2} = m \omega_r^2 r + m \omega^2 a \sin \omega t ,$$

where the first part represents the centrifugal force caused by the rotating drum, and the second part is connected with the rolling movement of the stringers.

When the difference between the magnetic attraction and centifugal forces, which are independent of time and perpendicular to the surface, equals the centrifugal force caused by the rolling movement, the stringers lose their contact with the surface

(11)
(9.4/14)
(10.1/14)

$$F_p = F_m - F_{c_1} = m\omega^2 a \sin\omega t \; .$$

If we assume that distance y remains so small that $F_p(y)$ stays constant, the maximum height, flying time, and rotating angle (about the centre of gravity) of the flights of magnetite clusters under the influence of high field frequencies can be calculated by employment of the following functions:

(12)
(10.5/11)

$$y_{\Sigma\,max} = \frac{ma^2\omega^2}{2F_p}$$

(13)
(10.6/14)
(10.1/14)

$$\begin{cases} t_\Sigma = 2\dfrac{ma\omega}{F_p}\cos\omega t_i \\ \sin\omega t_i = \dfrac{F_p}{ma\omega^2} \end{cases}$$

(14)
(10.7/14)

$$\varphi_{tot} = 2\frac{ma\omega^2}{F_p}\cos\omega t_i \; ,$$

where t_i is the time at which the stringer loses contact with the surface (at time $t=0$ the whole length of the stringer is touching the surface.)

Assuming that

F_p = 5 mp
a = 1 mm
ω = 100 · 2π(frequency is 100 c.p.s.)
m = 0.5 mg

the following values can be calculated:

$y_{\Sigma\,max}$ = 2 mm
t_Σ = 0.0124 s
φ_{tot} = 8 (= 485 °)

When the field frequency is 100 c.p.s., the maximum height during the flight of the cluster is 2 mm, and it makes 1.3 revolutions before it again hits the drum surface. The maximum time of flight is 0.0124 s.

Because F_p is always a function of y, the figures calculated above are probably not valid in practice, but they give a qualitative understanding of the behaviour of magnetite clusters under the influence of a rotating magnetic field. In this regard, LAURILA[14] states: "The outstretched clusters of magnetic powder, which always

have a limited length due to the heterogeneity of the magnetic field and other factors of a secondary nature, move on the surface under the influence of the rotating field, making revolutions round their tips which are in contact with the surface. At higher frequencies, the clusters make flights of shorter or longer duration above the surface, rotating about their centres of gravity. The powdered material on the surface thus forms like a cloud of moving and rotating clusters."

On increase in the field frequency, the stringer may be broken in the middle section. The break occurs when the centrifugal force, caused by the rotation of the stringer about its centre of gravity, and the attractive magnetic force acting in a direction along the long axis on any section perpendicular to the axis, are equal. The following function can be written:

(15)
(12.1/14)

$$a_{max} = \sqrt{\frac{2}{\mu_o s}} \cdot \frac{B}{\omega} ,$$

where B is the magnetic induction and s the bulk density of the stringer.

Assuming that

$$\begin{aligned} s &= 3000 \ kg/m^3 \\ B &= 0.1 \ \frac{Vs}{m^2} \\ \omega &= 100 \cdot 2\pi \end{aligned}$$

the calculated value of a_{max} is 3.66 mm. The length of the stringer is thus 7.3 mm.

LAURILA[14] believed that this calculated value was too great, as the simplifying assumptions made when deriving the functions did not quite correspond to reality. "The clusters are not quite a homogeneous material, their shape is not exactly an ovoid, the magnetic fields used in practice are seldom purely sinusoidal, many of the factors leading to the destruction of clusters have not been taken into account, etc. The result, nevertheless, describes one phenomenon that is observed in practice: the higher the frequencies the shorter the clusters."

If the stringers are all the time in contact with the drum surface, their linear velocity should be $2a\frac{\omega}{\pi}$. However, as at high frequencies they partly rotate freely above the surface, their velocity attains a maximum of

(16)
(12.2/14)

$$v_a = \frac{a\omega}{2} .$$

The velocity of the longest stringers is then

(17)
(12.3/11)

$$v_{a_{max}} = \frac{a_{max}\omega}{2} = \frac{1}{2} \sqrt{\frac{2}{\mu_o s}} \cdot B .$$

This velocity is constant and independent of field frequency.

6. The progression of magnetite particles under the influence of a rotating field

The speed at which magnetite particles travel on the drum surface under the influence of a rotating field can be determined by the following method. When the drum of a Laurila separator is locked, and the magnet wheel runs at a constant speed, a small amount of magnetite is introduced on to the shell and measurement made of the progression time of the magnetite clusters over a fixed distance.

Such measurements have already been described by the author in the paper: "Dry Magnetic Separation of Finely Ground Magnetite"[19]. JONES[20,21] made a more systematic investigation with respect to different size fractions of particles and different field frequencies. The results of this investigation indicate that:

a) Within the frequency range investigated, from 10 to 140 c.p.s., particle speed appears to become reasonably constant in the upper half of this range for any one particular particle size.
b) Relative particle speed (foot per second and cycle) is not constant, but decreases at higher frequencies.
c) Particle speed increases as particle size decreases to approximately 50 microns, and then falls off sharply.
d) Both frequency and particle size affect stringer length, and the efficiency of the separation process.

These "Jones-tests" were repeated with the 1 m diameter separator.

The experiments showed that there is an appreciable divergence between the speed of the individual clusters even within one Tyler screen class. The time of both the fastest and the slowest particles was thus measured for a progression of only one metre. Each experiment was repeated five to ten times.

The results are given in Tables 5 and 6 and in Figures 4-7. From the results the following conclusions can be drawn:

- The velocity of the stringers increases rapidly with an increasing field frequency up to 50-75 c.p.s. On logarithmic paper this part of the curve is almost straight, c.f. Fig. 4.
- Between 50-150 c.p.s., the change in the speed is less, the curves in Fig.4 being nearly flattened out.
- Above 150 c.p.s. the velocity of the fastest stringers increases again except as regards the coarse grain sizes, whose velocity increases more gradually, or even decreases when the field frequency is over 300 c.p.s.
- The velocity of the stringers rises with increasing grain size, if the grain size is less than 50 microns. When the grain size is over 50 microns, the velocity seems to be independent of the grain size except at field frequencies of more than 200 c.p.s. where the velocity decreases with increasing grain size, c.f. Fig. 5.
- The velocity/field frequency curves, Fig.6, using the same grain size of Kärväsvaara, Otanmäki, and Porkonen magnetite, show that the magnetite of Kärväsvaara is the fastest, followed by those of Otanmäki and Porkonen, respectively. Tests with unscreened magnetite concentrate of these same ores gave indentical results, c.f. Fig. 7.

Table 5.

The velocity of the fastest and slowest stringers of Kärväsvaara magnetite on drum surface under the influence of a rotating magnetic field at different field frequencies.

	Grain size		Particle speed, cm/s, at different field frequencies																					
	Tyler mesh	Microns	10 c.p.s.		25 c.p.s.		50 c.p.s.		80 c.p.s.		110 c.p.s.		150 c.p.s.		200 c.p.s.		260 c.p.s.		370 c.p.s.		440 c.p.s.		480 c.p.s.	
			f[1]	s[2]	f	s	f	s	f	s	f	s	f	s	f	s	f	s	f	s	f	s	f	s
Sieve	48/70	294/209	7.7	7.0	16.7	14.7	23.4	18.9	25.7	19.6	28.8	21.8	33.6	28.0	42.8	35.3	46.2	38.0	50.8	41.8	47.6	40.8		
	70/100	209/146	7.8	6.9	15.6	13.8	21.5	17.0	26.0	19.1	28.0	20.8	33.3	27.8	41.2	34.8	44.7	38.9	49.5	44.4	49.0	41.0		
	100/150	146/105	6.9	6.1	15.9	13.6	22.8	19.0	25.4	20.2	28.2	22.4	31.3	26.1	40.8	34.3	48.8	38.6	54.5	44.1	57.2	46.6		
	150/200	105/74	6.8	5.8	14.3	12.6	22.0	18.2	25.9	19.9	28.2	21.5	31.4	24.2	41.7	31.4	48.5	37.7	58.8	46.7	61.0	50.0		
	200/270	74/54	5.8	4.7	13.5	11.9	21.7	18.6	25.9	20.9	28.0	22.2	30.9	24.1	40.2	31.2	51.3	42.6	53.6	50.2	60.0	51.1		
	270/400	54/37	4.3	3.6	10.4	8.8	19.1	15.1	26.3	19.4	28.4	22.4	31.8	25.1	38.0	30.0	47.2	38.0	60.7	48.8	62.2	52.6		
Sub-sieve		37/26	5.4	4.8	12.4	11.9	21.4	17.7	28.3	25.0	30.7	27.6	33.0	28.1	38.5	29.3	43.8	31.8	55.4	33.6			64.8	33.4
		26/18.5	4.8	3.9	10.5	9.1	17.2	14.8	23.9	21.0	27.1	23.6	30.3	26.2	33.3	28.8	37.1	27.7	48.5	32.1			54.5	35.2
		18.5/13.0	3.8	3.3	7.6	6.9	16.0	14.3	23.1	20.8	26.4	23.3	28.8	27.1	31.5	29.0	38.5	31.8	47.0	39.7			50.0	39.2
		13.0/ 9.3	3.6	3.2	7.7	6.7	13.8	12.0	19.0	16.8	23.5	21.0	27.4	24.5	30.8	27.7	34.0	30.3	41.1	34.4			46.6	37.1
		9.3/ 6.5	3.3	2.8	6.4	5.7	11.5	10.2	16.8	15.0	20.2	17.5	25.0	19.9	29.1	23.8	32.8	25.9	40.3	31.2			44.7	34.1
		- 6.5	3.2	2.5	6.2	4.6	10.4	8.3	16.0	12.4	19.0	14.5	23.2	17.0	26.7	18.8	30.4	20.8	36.7	24.0			43.3	25.0

1) f means fastest particle groups

2) s " slowest " "

Table 6.

The velocity of the fastest stringers of Kärväsvaara magnetite at a distance of 10 mm from drum surface under the influence of a rotating magnetic field at different field frequencies.

Grain size		Particle speed, cm/s, at different field frequencies							
Tyler mesh	Microns	25 c.p.s.	50 c.p.s.	80 c.p.s.	110 c.p.s.	150 c.p.s.	200 c.p.s.	260 c.p.s.	370 c.p.s.
48/70	294/209	29.4	32.3	33.9	35.8	38.5	37.8	40.0	43.5
70/100	209/146	28.6	29.4	35.8	35.8	37.1	38.5	39.2	43.5
100/150	146/105	27.8	28.6	34.5	34.5	35.8	38.5	38.5	41.7
150/200	105/74	27.0	27.0	31.3	33.3	34.5	38.5	39.2	42.6
200/270	74/54	25.0	27.8	30.8	33.3	33.3	37.1	36.4	38.5
270/400	54/37	19.6	25.7	29.0	31.3	33.3	35.8	39.2	38.5

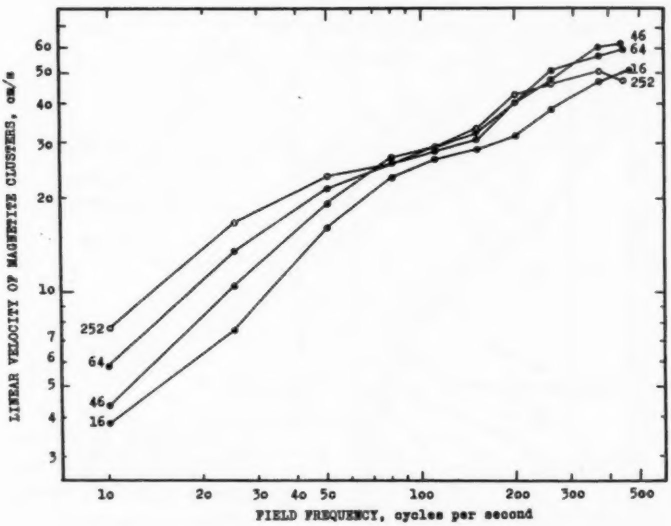


Fig.4. Velocity of progression of the fastest magnetite clusters under the influence of a rotating magnetic field as a function of field frequency. The numbers by the curves indicate average grain sizes in microns.

The above results are in agreement with those presented by JONES, except for item c) which describes the dependence of velocity on grain size. In his later investigations, JONES[22] obtained similar results to those given in Fig. 5. These later tests were made with a 125 mm diameter separator with a shell concentric with the magnet wheel. The former tests were made with an eccentric Cavanagh separator, c.f. Fig. 1 C. The biggest and fastest stringers probably dropped away from the shell at the section where the distance between shell and magnet wheel was greatest and the erroneous results can be attributed to this phenomenon. The magnetite was also thrown off in the tests made with the Laurila separator: at high frequencies, new material had to be introduced on the drum for each individual test.

In order to investigate the influence exerted by the strength of the magnetic field on the progression of magnetite stringers, comparative tests were made after the separator drum had been covered with a rubber sheet 10 mm thick. This cover decreased the flux density of separator No.1 from 1100 to 620 Gauss , c.f. Fig. 2. The rubber sheet was painted with the same paint as that used on the plastic drum in the tests presented in Table 5.

The results are given in Table 6. On comparison with the results given in Table 5, it is obvious that a decreasing field strength increases the velocity of the stringers

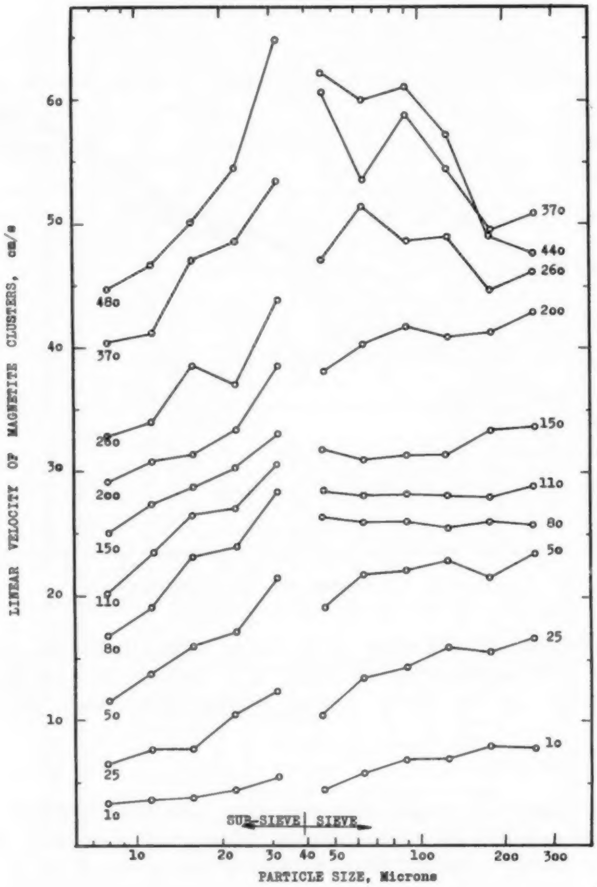


Fig. 5. Velocity of progression of the fastest magnetite clusters under the influence of a rotating magnetic field as a function of grain size. The numbers by the curves indicate different field frequencies in cycles per second.

at field frequencies under 150 c.p.s. but decreases it when the field frequency is over 150 c.p.s.

If it is assumed that during movement the stringers are in contact with the shell, it is possible to calculate the length of one stringer. If a further assumption is made that a stringer is formed by one elongated row of grains, it is possible to calculate the number of particles in it. (One stringer progresses twice its length per cycle. Microscopic measurements show that the breadth and the length of a magnetite grain have a ratio of 0.7; thus the grain size obtained by screening must be divided

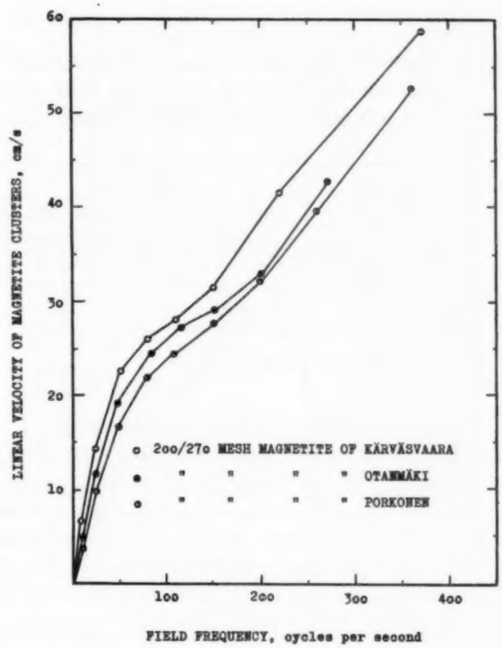


Fig. 6. Velocity of progression of 200/270 mesh magnetite of Kärväsvaara, Otanmäki and Porkonen ores under the influence of a rotating magnetic field as a function of field frequency.

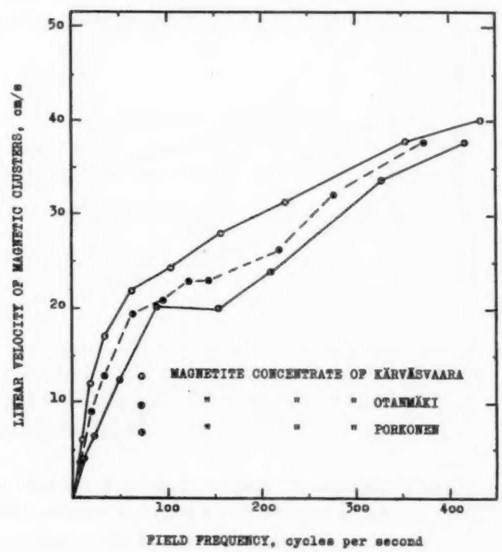


Fig. 7. Velocity of progression of unscreened magnetite of Kärväsvaara, Otanmäki and Porkonen ores under the influence of a rotating magnetic field as a function of field frequency.

Table 7.

Length of magnetite clusters and number of magnetite particles in one cluster under the influence of a rotating field of 50 c. p. s. at different grain sizes; calculated from particle velocity values (fastest) in tables 5 and 6.

	Grain size, microns	On drum surface		At a distance of 10 mm from drum surface	
		Length of cluster, mm	Number of grains in one cluster	Length of cluster, mm	Number of grains in one cluster
Sieve	294/209	2.34	6.5	3.23	9
	209/146	2.15	8.5	2.94	12
	146/105	2.28	13	2.86	16
	105/74	2.20	17	2.70	21
	74/54	2.17	24	2.78	31
	54/37	1.91	29	2.57	39
Sub-sieve	37/26	2.14	47		
	26/18.5	1.72	54		
	18.5/13	1.60	71		
	13/ 9.3	1.38	87		
	9.3/ 6.5	1.15	102		

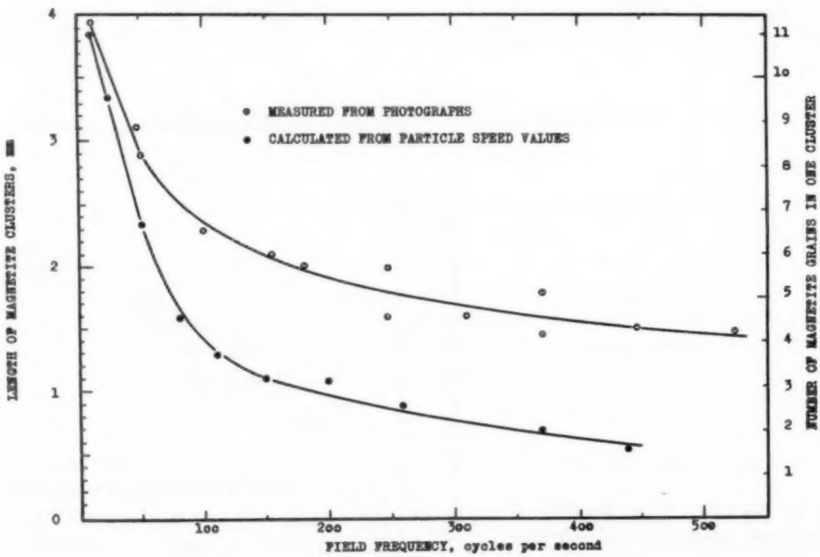
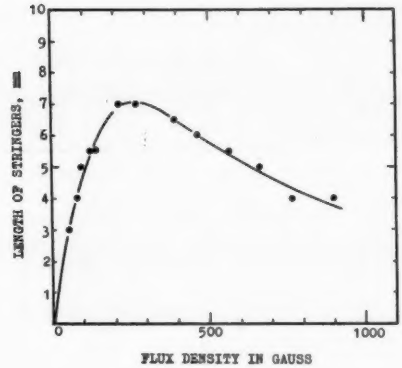


Fig. 8. Length of longest magnetite clusters and number of magnetite grains in one cluster under the influence of a rotating field as a function of field frequency. Test material 48/70 mesh magnetite of Kärväsvaara.

Fig. 9. Length of longest magnetite clusters (average length of ten clusters) on separator shell, after the magnet wheel has come to a standstill, as a function of flux density. Test material 48/70 mesh magnetite of Kärväsvaara.



by 0.7 to get the length of a grain.) The calculated values are given in Table 7, and Fig. 8. The length of a stringer decreases with decreasing grain size, but the number of particles in it rises. Increasing field frequency decreases the length of the stringer and the number of particles in it.

According to Tables 5 and 6, the length of the clusters seems to be increased by decreasing field strength at field frequencies under 150 c.p.s. but decreased at higher field frequncies. To prove the first statement, the length of magnetite clusters was measured at different distances from the drum surface after their movement had been arrested by bringing the magnet wheel to a standstill. The values as a function of flux density are given in Fig. 9. They show that at low field frequencies the length of the clusters is in fact inversely proportional to the field

Table 8.

Length of the clusters of four grain sizes of Otanmäki and Porkonen magnetite measured on the shell and at a distance of 10 mm from drum surface after the magnet wheel had come to a standstill (average length of twenty clusters).

Grain size, microns	Length of magnetite cluster, mm			
	On drum surface		At a distance of 10 mm from drum surface	
	OTANMÄKI	PORKONEN	OTANMÄKI	PORKONEN
294/209	4.50	3.24	5.93	4.29
209/146	4.03	2.80	5.17	3.66
146/ 74	3.55	2.00	4.48	2.66
74/ 54	2.05	1.75	3.25	1.97

Table 9.

Some data concerning the photography of particle movement at different field frequencies with a Fastax high speed motion camera.

Film no.	Field frequency c. p. s.	Picture taking rate, p. p. s.	Aperture of camera, f
1	10	1400	5.6
2	30	1400	5.6
3	50	1400	5.6
4	60	1400	5.6
5	70	2500	3.5
6	80	2500	3.5
7	90	2500	3.5
8	100	2500	3.5
9	120	2500	3.5
10	150	3500	3.5
11	200	3500	3.5
12	300	5000	3.5
13	400	5000	3.5
14	Millimeter scale for size comparison		

strength if the flux density is over 300 Gauss. At lower flux densities, the length of the clusters rises with increasing field strength.

With different magnetites, the length of stringers varies. The measurements were made with four different grain sizes of Otanmäki and Porkonen magnetites. The results are given in Table 8. The stringers of Otanmäki magnetite are longer than the corresponding clusters of Porkonen, and consequently Otanmäki magnetite has a higher speed of progression in Figures 6 and 7 than Porkonen.

7. Photographing magnetite particles in a rotating field

The purpose of the photography was that of recording the behaviour of magnetite powder on the drum surface at different field frequencies. The test procedure was nearly the same as that employed in the "Jones-tests." In order to keep the rotating stringers in focus, the drum was rotated at an appropriate speed in the direction opposite to the progression of clusters. ·

Forty pictures were taken with the Contaflex III camera at field frequencies of 9 to 525 c.p.s. of grain size 48/70 mesh, 0.294/0.209 mm, of repeatedly cleaned Kärväsvaara magnetite.

Altogether, thirteen high-speed motion films were taken of the tumbling movement of grain size 70/100 mesh, 0.209/0.146 mm, of Kärväsvaara magnetite. The test

A) Field frequency 22 c.p.s., all clusters remain on the drum surface.

B) Field frequency 60 c.p.s., the stringers begin to jump off the surface and some are flying in the air.

C) Field frequency 100 c.p.s., more flying clusters are to be seen.

D) Field frequency 156c.p.s., the first individual particle flying away from the field is shown on the right.

E) Field frequency 247 c.p.s., the length of the stringers is clearly decreased.

F) Field frequency 370 c.p.s., nearly all the clusters are in the air, off the drum surface, and rotating about their centres of gravity.

G) Field frequency 446 c.p.s., there are still clusters and they are orientated along the field lines; many particles flying off.

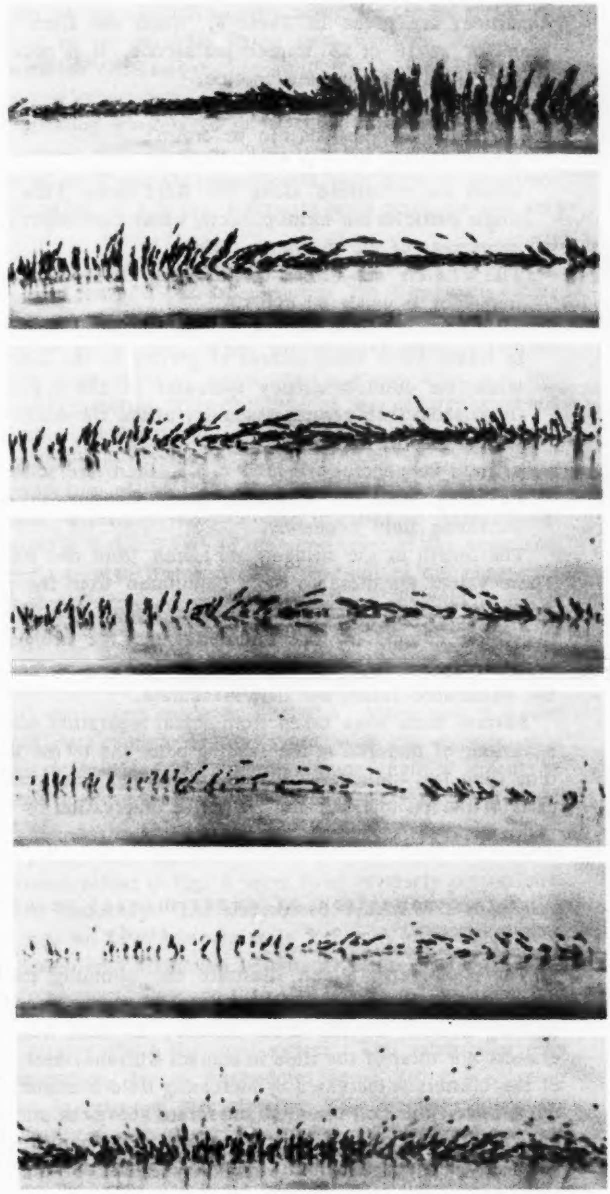


Fig. 10. Photographs of magnetic clusters under the influence of a rotating magnetic field at different field frequencies. Test material 48/70 mesh Kärväsvaara magnetite.

conditions are given in Table 9. When the films are projected with a normal projector at 16 or 24 frames per second, it is possible to see the movement of magnetite stringers in slow motion.

From careful observation of the fims and the individual photographs, Fig. 10, the following conclusions can be drawn:

- In all pictures, even at frequencies over 500 c.p.s., there are elongated stringers, which are orientated along the field lines. Thus, magnetite does not occur as single particles but forms clusters, whose movement seems to follow the rotational movement of the magnetic field.
- The clusters are almost continuously in contact with the shell when the field frequency is under 50 c.p.s.
- At frequencies over 50 c.p.s., the stringers begin to jump off the drum, and to rotate about their centres of gravity in the air.
- When the field frequency increases to 120 c.p.s., the clusters rotate several times about their centres of gravity above the drum surface. Many clusters make long flights in the air.
- At field frequencies over 150 c.p.s. there are some particles and clusters which fly away from the magnetic field, the number of these particles rising with increasing field frequency.

The length of the stringers measured from the photographs are given in Fig. 8. These values are close to those calculated from the particle speed when the field frequency is under 50 c.p.s. At higher frequencies, the measured values are greater than those calculated. The assumption that the stringers are continuously in contact with the shell during the progression is not true at frequencies over 50 c.p.s., and the calculated values are thus inaccurate.

Several films were taken from actual separation tests in order to investigate the behaviour of material at the feeding point and on the drum surface. However, these tests were less indicative. Non-magnetic and dusty material shadowed the interesting parts of the photographs and prevented observation of the movements of magnetite.

8. A comparison of experimental results and theoretical study

The photographs which illustrate the tumbling movements of magnetite in a rotating field have proved that magnetite powder does form a cloud of moving and rotating clusters on the drum surface. At field frequencies under 50 c.p.s., the clusters are most of the time in contact with the shell, and thus the linear velocity of the clusters is increased by increasing field frequency. At higher field frequencies, the clusters jump off the shell and rotate above the drum surface about their centres of gravity. Thus their linear velocity is no longer directly proportional to the field frequency. The speed/field frequency curves of the "Jones-tests" assume a more horizontal plane. The steeper part of the curve for the fastest clusters at frequencies over 150 c.p.s. probably depends on the additional speed acquired by some rotating particle groups when they hit the shell surface in suitable positions, and/or when they fly away from larger clusters in the direction of the progression.

The horizontal or falling part of the speed/frequency curve for coarse grains at high frequencies can be explained by the particles flying away from the magnetic field. The loss of magnetic particles decreases the length of the stringers, and thus slows down the speed of the linear progression.

At higher frequencies, the rotating clusters seem to be in the air for most of the time and make only light contact with the drum. This fact has also been proved in practice. The dry separators in the Otanmäki concentrator have been in operation for about four years. The shells made of 1.2 mm austenitic steel plate are not yet worn out.

Visual observations of the slowly tumbling magnetite clusters show that when there is so much material on the drum surface that the clusters run into each other, rearrangement of the material in a cluster occurs. A cluster may accept new groups of magnetite grains on its top or on its side. When an overisize stringer tumbles further it is divided into two or more stringers which contain grains from both the original stringer and the additional material. This phenomenon was clearly observed when a part of the magnetite material was painted white. A cluster which does not strike other clusters remains unchanged.

The differences in linear velocities of the magnetites of Otanmäki, Kärväsvaara and Porkonen ores in "Jones-tests" depend on the difference in effective permeability. The Fe-contents of the magnetites in Table 2 vary in the same order as the velocities in Fig. 6 and the lengths of clusters in Table 8. The readings of the magnetite analyzer should be related to the effective permeabilities. These readings with the 200/270 mesh magnetite of Kärväsvaara, Otanmäki and Porkonen ores were 202, 168 and 122 respectively.

The observations made from the films, photographs, and "Jones-tests" are in fair agreement with the theoretical statements made by LAURILA. There are, however, some functions and calculated data which do not agree with the experimental results. For example, according to function (15), the maximum length of magnetite stringers should be directly proportional to the flux density, and inversely proportional to the field frequency. The results given in Tables 5 and 6 indicate that the length of the stringers is directly proportional to the flux density only at field frequencies over 150 c.p.s., and the measured values in Fig. 8 seem to be inversely proportional to the third root of the field frequency. The calculated length of a magnetite cluster at 100 c.p.s. is 7, 3 mm but it is approximately 2.5 mm on measurement. The 7.3 mm figure and the calculated maximum height of 2 mm of the flight of a rotating cluster are also contradictory. Function (15) is based on the assumption that centrifugal force will break the clusters in the middle section when they rotate freely about their centres of gravity above the shell surface. This assumption may be correct at high field frequencies, but at frequencies under 150 c.p.s. other phenomena seem to dominate in breaking the clusters. The magnetic attractive force presses the stringers so firmly against the shell surface that they break at their base when the rotating field forces them to rotate. Visual observarions verify this statement. In Fig. 10 are some stringers which are bent at the base.

This phenomenon expalains also the shape of the curve in Fig. 9. An increasing field strength increases the "tensile strength" of the clusters until magnetic saturation is reached. According to Fig. 9 saturation is attained at a flux density of 300 Gauss

where the length of the clusters has its maximum value. When the field strength increases further, the pressure against the drum surface increases, but because the strength of the clusters remains unchanged the length of the stringers is decreased.

The statement that the linear speed of rotating magnetite clusters is constant at higher field frequencies, c.f. function 17, does not quite hold although the curves in Figures 4 and 7 are almost flattened out between 100 and 200 c.p.s.

However, the discrepancies mentioned above have no notable importance in comprehension of the phenomena in dry separation. They may be due in part to the possibility of inaccuracy in the values assumed in the calculations, and to the simplifications introduced when formulating the functions. One of the assumptions made in connection with functions 12, 13 and 14 was that the length of the stringer is so small in comparison with the pole distance that the magnetic field is also homogeneous in the direction perpendicular to the drum surface. This is not in fact true because the magnitude of the magnetic field varies very much within the length of a stringer. In order to investigate how long particles will rotate in the rotating field, a test was made with cut pieces of 0.8 mm Ø iron wire. Pieces of a maximum length of 13 and 8 mm were rotated on the drum surfaces of 1.0 m and 0.4 m diameter separators, respectively. The corresponding ratios between the maximum length and the pole distances were 0.25 and 0.22.

SEPARATION TESTS

The tests and films analyzed above have shown that the behaviour of magnetic particles in a rotating magnetic field changes with increasing field frequency. To determine what influence these changes have on magnetic separation, several tests were made with natural ores.

Apart from field frequency, the direction of rotation of the magnet wheel, the rotating speed of the drum, the feeding capacity, and the grinding fineness were also treated as variables. The results are given in Tables 10-12.

There is some disagreement between the results obtained in separate tests. It proved difficult to keep all the other variables constant (especially the feed rate) while investigating the effect of one definite variable. The amount of the ore sample for each test was 10 kg, resulting in a feeding time of only 7 seconds at a rate of 5 ton/h. The large number of tests carriend out should compensate for the inaccuracies in values.

The most interesting effects found in Tables 10-12 were checked by further tests with several successive separations, as given in Tables 13-15.

The results are examined in what follows from the viewpoint of those variables which can be regulated or changed in a separation test.

9. Effect of magnetic attractive force

The magnetite powder on the shell is influenced by a magnetic attractive force, centrifugal force and gravitational force. Because the gravitational force is constant and much smallerr than the two others, its effect is not discussed below.

The magnetic fields of separators Nos. 1 and 2 differed, the former having a higher field strength but a lower gradient than the latter, c. f. Fig. 2. As shown by function (4), magnetic attractive force depends on both.

Table 10.

Fe_3O_4 - grade and -recovery in separation tests of Otanmäki ore with field freq
rate as variables. Tests were made with samples with grinding fineness of 5

Drum speed, r.p.m.	Field frequency, c.p.s.		Magnetite progresses in same direction as drum								
			350		125		75		50		3
		Fe_3O_4, %	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade
60	Magnet wheel speed, r.p.m. Rotation direction		640 opp. dir. 1)		190 opp. dir.		80 opp. dir.		40 opp. dir.		(
	Feed rate 5 ton/h/dm	C 3)	72.5	93.4	77.1	96.8	75.9	97.2	71.8	97.3	61.6
		T 4)	3.3	6.6	1.7	3.2	1.5	2.8	1.4	2.7	1.4
	Feed rate 3 ton/h/dm	C	82.7	92.3	81.0	96.9	77.6	97.0	75.0	97.3	70.9
		T	4.0	7.7	1.6	3.1	1.5	3.0	1.4	2.7	1.4
	Feed rate 1 ton/h/dm	C	86.9	91.3	86.6	97.0	79.7	96.9	81.4	97.3	75.0
		T	4.6	8.7	1.5	3.0	1.6	3.1	1.3	2.7	1.5
100	Magnet wheel speed, r.p.m. Rotation direction		600 opp. dir.		150 opp. dir.		50 opp. dir.		0		4 san
	Feed rate 10 ton/h/dm	C									
		T									
	Feed rate 5 ton/h/dm	C	82.7	90.6	86.9	96.3	79.3	96.5	80.1	96.4	71.8
		T	4.6	9.4	2.0	3.7	1.8	3.5	1.9	3.6	1.7
	Feed rate 3 ton/h/dm	C	87.6	88.5	86.9	96.0	82.7	96.3	80.1	96.9	73.3
		T	5.5	11.5	2.1	4.0	1.9	3.7	1.6	3.1	1.5
	Feed rate 1 ton/h/dm	C	88.2	86.6	87.8	96.7	86.1	96.3	81.8	98.0	75.9
		T	6.2	13.4	1.7	3.3	1.9	3.7	1.0	2.0	1.5
150	Magnet wheel speed, r.p.m. Rotation direction		550 opp. dir.		100 opp. dir.		0		50 same dir.		9 san
	Feed rate 5 ton/h/dm	C	92.0	55.0	89.5	81.4	83.5	92.3	87.8	89.6	85.2
		T	13.6	45.0	10.0	18.6	3.6	7.7	5.3	10.4	5.2
	Feed rate 3 ton/h/dm	C	92.4	44.7	92.9	87.4	86.9	94.1	88.6	89.8	86.9
		T	22.2	55.3	6.1	12.6	2.8	5.9	5.4	10.2	2.5
	Feed rate 1 ton/h/dm	C	90.3	58.3	92.3	93.1	86.5	94.5	88.6	95.1	86.1
		T	15.0	41.7	3.4	6.9	2.6	5.5	2.5	4.9	2.1
200	Magnet wheel speed, r.p.m. Rotation direction				0		50 same dir.		100 same dir.		san
	Feed rate 1 ton/h/dm	C			86.9	52.4	85.2	59.6	85.2	52.0	83.1
		T			20.4	47.6	18.2	40.4	20.4	48.0	18.3

1) opp. dir. means that magnet wheel and drum rotate in opposite directions

2) same dir. means that magnet wheel and drum rotate in the same direction

3) C = concentrate

4) T = tailing

10.

frequency, direction of rotation of magnet wheel, drum speed, and feed of 50 % minus 200 mesh, c.f. Table 4, and with separator No.1.

		Magnetite progresses in opp. direction to drum				
30	0	25	50	75	125	350
Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.
0	60 same dir. 2)	110 same dir.	160 same dir.	210 same dir.	310 same dir.	760 same dir.
61.6 97.6 1.4 2.4	34.5 99.6 1.1 0.4	53.8 98.1 1.3 1.9	66.9 97.5 1.4 2.5	67.5 97.8 1.3 2.2	77.1 97.3 1.4 2.7	79.3 96.9 1.6 3.1
70.9 97.5 1.4 2.5	36.0 99.4 1.0 0.6	60.2 98.0 1.3 2.0	72.9 97.2 1.5 2.8	70.9 97.5 1.4 2.5	80.1 97.1 1.5 2.9	79.7 96.9 1.6 3.1
75.0 97.3 1.5 2.7	53.8 98.1 1.0 1.9	72.5 97.8 1.2 2.2	79.6 97.2 1.4 2.8	81.0 97.0 1.5 3.0	83.5 97.0 1.5 3.0	84.4 96.7 1.6 3.3
40 same dir.	100 same dir.	150 same dir.	200 same dir.	250 same dir.	350 same dir.	800 same dir.
			58.9 95.2 3.0 4.8		66.1 96.5 2.0 3.5	
71.8 97.0 1.7 3.0	42.0 99.0 1.2 1.0	46.0 97.6 1.4 2.4	72.5 97.1 1.6 2.9	75.0 97.1 1.6 2.9	80.1 97.0 1.5 3.0	81.0 95.9 2.1 4.1
73.3 96.8 1.5 3.2	43.2 98.7 1.3 1.3	64.0 97.8 1.3 2.2	78.6 97.7 1.4 2.3	78.4 97.1 1.5 2.9	81.8 97.0 1.6 3.0	86.1 95.6 2.3 4.4
75.9 96.8 1.5 3.2	63.1 98.1 1.2 1.9	76.7 97.5 1.4 2.5	76.7 96.8 1.6 3.2	83.5 96.5 1.8 3.5	86.9 97.1 1.5 2.9	86.9 95.3 2.3 4.7
90 same dir.	150 same dir.	200 same dir.	250 same dir.	300 same dir.	400 same dir.	850 same dir.
85.2 89.4 5.2 10.6	61.4 97.1 1.7 2.9	80.5 93.6 3.0 6.4	84.4 91.7 3.9 8.3	86.1 96.2 1.9 3.8	89.5 95.8 2.1 4.2	91.2 86.1 6.6 13.9
86.9 95.2 2.5 4.8	75.4 95.8 2.2 4.2	81.0 93.4 3.2 6.6	82.7 88.8 5.5 11.2	88.6 96.2 1.9 3.8	88.6 96.0 2.0 4.0	92.4 80.2 9.1 19.8
86.1 96.1 2.1 3.9	75.9 96.8 1.6 3.2	82.7 96.0 2.0 4.0	84.0 93.8 3.0 6.2	88.6 95.4 2.3 4.6	92.0 95.1 2.5 4.9	91.6 70.0 12.4 30.0
140 same dir.	200 same dir.	250 same dir.	300 same dir.	350 same dir.	450 same dir.	
83.1 58.3 18.3 41.7	78.8 72.3 16.5 27.7	82.7 46.9 24.3 53.1	82.7 36.1 23.4 63.9	87.4 59.8 18.0 40.2	88.3 54.3 18.3 45.7	

Table

Fe_3O_4 - grade and-recovery in separation tests of Otanmäki ore,
of rotation of magnet wheel, drum speed, and feed

Drum speed, r.p.m.	Field frequency, c.p.s.		Magnetite progresses in same direction as drum							
			350		125		75		50	
		Fe_3O_4, %	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.
60	Magnet wheel speed, r.p.m. Rotation direction		640 opp. dir.[1]		190 opp. dir.		90 opp. dir.		40 opp. dir.	
	Feed rate 5 ton/h/dm	C[3] T[4]	62.3 2.4	95.8 4.2	47.0 1.6	97.8 2.2	50.0 1.5	97.7 2.3	52.9 1.5	97.6 2.4
	Feed rate 1 ton/h/dm	C T	78.9 1.8	96.3 3.7	68.2 1.7	96.5 3.5	65.7 1.6	96.8 3.2	63.1 1.7	96.7 3.3
100	Magnet wheel speed, r.p.m. Rotation direstion		600 opp. dir.		150 opp. dir.		50 opp. dir.		0	
	Feed rate 5 ton/h/dm	C T	75.0 5.6	88.2 11.8	71.8 2.0	95.8 4.2	64.8 1.8	96.4 3.6	61.0 1.9	96.4 3.6
	Feed rate 1 ton/h/dm	C T	80.1 3.2	93.2 6.8	74.2 1.6	96.6 3.4	70.9 1.8	96.3 3.7	64.4 1.7	96.6 3.4
150	Magnet wheel speed, r.p.m. Rotation direction		550 opp. dir.		100 opp. dir.		0		50 same dir.	
	Feed rate 5 ton/h/dm	C T	76.7 20.5	44.8 55.2	73.3 12.4	69.3 30.7	72.2 6.9	84.6 15.4	65.4 14.8	62.4 37.6
	Feed rate 1 ton/h/dm	C T	76.7 19.8	46.3 53.7	75.5 4.3	90.3 9.7	72.2 3.1	93.3 6.7	68.2 5.3	90.4 9.6

1) opp. dir. means that magnet wheel and drum rotate in opposite sirections

2) same dir. means that magnet wheel and drum rotate in the same direction

3) C = concentrate

4) T = tailing

11.

grinding fineness 70 % minus 200 mesh, with field frequency, direction rate as variables. Tests were made with separator No.1.

				Magnetite progresses in opp. direction to drum									
30		0		25		50		75		125		350	
Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.
0		60 same dir. 2)		110 same dir.		160 same dir.		210 same dir.		310 same dir.		760 same dir.	
48.3	97.6	29.1	99.7	47.8	98.2	52.5	97.8	53.8	97.7	52.1	97.9	52.5	97.7
1.6	2.4	1.8	0.3	1.3	1.8	1.4	2.2	1.4	2.3	1.4	2.1	1.6	2.3
56.3	97.2	29.4	99.5	56.3	97.5	63.1	97.3	66.1	97.2	69.1	96.9	72.5	97.1
1.6	2.8	1.7	0.5	1.4	2.5	1.4	2.7	1.4	2.8	1.5	3.1	1.5	2.9
40 same dir.		100 same dir.		150 same dir.		200 same dir.		250 same dir.		350 same dir.		800 same dir.	
54.6	96.2	32.4	98.8	54.6	97.3	58.9	97.3	61.4	97.4	64.8	97.1	66.1	96.3
2.2	3.8	2.1	1.2	1.6	2.7	1.5	2.7	1.4	2.6	1.5	2.9	2.0	3.7
59.7	96.6	41.8	97.9	58.9	97.1	65.7	96.6	68.2	96.5	73.3	96.6	75.9	96.3
1.8	3.4	1.7	2.1	1.6	2.9	1.7	3.4	1.7	3.5	1.6	3.4	1.8	3.7
90 same dir.		150 same dir.		200 same dir.		250 same dir.		300 same dir.		400 same dir.		850 same dir.	
62.3	51.0	48.4	85.7	59.7	68.2	63.1	90.5	66.5	96.9	71.8	95.4	75.5	85.7
18.2	49.0	8.3	14.3	13.4	31.8	4.6	9.5	1.5	3.1	2.2	4.6	6.6	14.3
65.3	84.2	55.0	95.5	62.3	84.1	67.4	87.9	71.8	94.0	73.0	95.5	79.7	86.9
7.2	15.8	2.6	4.5	7.4	15.9	5.6	12.1	2.8	6.0	2.1	4.5	5.9	13.1

Table 12.

Fe_3O_4 - grade and -recovery in separation tests of Otanmäki ore, grind
of rotation of magnet wheel, drum speed, and feed rate

			Magnetite progresses in same direction as drum								
Drum speed, r.p.m.	Field frequency, c.p.s.		350		125		75		50		3
		Fe_3O_4, %	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade
60	Magnet wheel speed, r.p.m.		640		190		90		40		0
	Rotation direction		opp. dir. 1)		opp. dir.		opp. dir.		opp. dir.		
	Feed rate 5 ton/h/dm	C 3)	42.9	96.2	41.4	96.8	42.6	96.5	43.2	96.3	44.1
		T 4)	3.7	3.8	2.5	3.2	2.4	3.5	2.5	3.7	2.6
	Feed rate 1 ton/h/dm	C	71.4	96.0	58.4	95.8	55.5	95.8	52.9	95.9	47.8
		T	2.2	4.0	2.2	4.2	2.3	4.2	2.4	4.1	2.4
100	Magnet wheel speed, r.p.m.		600		150		50		0		4
	Rotation direction		opp. dir.		opp. dir.		opp. dir.				sam
	Feed rate 5 ton/h/dm	C	60.6	72.1	56.3	86.0	52.5	92.5	49.5	93.4	42.6
		T	13.2	27.9	7.9	14.0	4.0	7.5	3.8	6.6	5.8
	Feed rate 1 ton/h/dm	C	71.4	93.3	62.7	94.9	58.0	95.4	54.6	94.7	51.3
		T	3.6	6.7	2.5	5.1	2.4	4.6	2.7	5.3	3.1
150	Magnet wheel speed, r.p.m.		550		100		0		50		9
	Rotation direction		opp. dir.		opp. dir.				same dir.		sam
	Feed rate 5 ton/h/dm	C	67.8	28.3	59.7	33.3	55.5	31.3	53.8	33.9	50.4
		T	24.9	71.7	22.2	66.7	23.1	68.5	22.2	66.1	23.7
	Feed rate 1 ton/h/dm	C	68.2	50.5	60.1	87.9	57.2	89.5	53.8	82.9	52.9
		T	20.2	49.5	5.6	12.1	5.1	10.5	8.0	17.1	14.4

1) opp. dir. means that magnet wheel and drum rotate in opposite directions

2) same dir. means that magnet wheel and drum rotate in the same direction

3) C = concentrate

4) T = tailing

ble 12.

ore, grinding fineness 90 % minus 200 mesh, with field frequency, direction
eed rate as variables. Tests were made with separator No. 1.

n					Magnetite progresses in opp. direction to drum											
	30		0		25		50		75		125		350	
.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.
	0		60 same dir. 2)		110 same dir.		160 same dir.		210 same dir.		310 same dir.		760 same dir.	
3	44.1	96.2	28.5	94.6	33.0	92.2	35.7	93.9	36.0	94.8	36.3	97.1	38.4	98.5
7	2.6	3.8	15.6	5.4	8.4	7.8	5.7	6.1	5.1	5.2	3.1	2.9	2.2	1.5
9	47.8	96.1	29.4	97.9	44.4	97.4	52.8	96.7	55.2	96.4	59.4	95.8	62.7	96.6
1	2.4	3.9	4.1	2.1	2.0	2.6	2.0	3.3	2.1	3.6	2.3	4.2	2.2	3.4
	40 same dir.		100 same dir.		150 same dir.		200 same dir.		250 same dir.		350 same dir.		800 same dir.	
4	42.6	91.3	29.4	87.8	39.3	84.8	42.9	82.4	45.6	83.2	49.2	81.9	48.3	92.6
6	5.8	8.7	16.0	12.2	10.2	15.2	10.0	17.6	9.2	16.8	9.3	18.1	5.7	7.4
7	51.3	94.4	39.6	94.8	49.5	96.4	54.6	96.1	58.0	95.9	61.4	96.1	69.5	96.1
3	3.1	5.6	3.9	5.2	2.3	3.6	2.2	3.9	2.2	4.1	2.0	3.9	2.2	3.9
	90 same dir.		150 same dir.		200 same dir.		250 same dir.		300 same dir.		400 same dir.		850 same dir.	
9	50.4	27.2	35.7	52.1	47.8	48.3	49.5	80.6	55.0	89.3	55.5	92.5	62.7	87.3
1	23.7	72.8	21.9	47.9	19.9	51.7	9.7	19.4	5.8	10.7	4.1	7.5	7.0	12.7
9	52.9	65.9	41.2	85.9	50.4	80.3	54.6	90.3	58.0	95.1	61.8	95.6	68.6	95.3
1	14.4	34.1	8.4	14.1	9.7	19.7	5.1	9.7	2.6	4.9	2.2	4.4	2.6	4.7

If we assume that the term $\frac{\mu_a - 1}{1 + N(\mu_a - 1)} \cdot \frac{2\pi V}{\mu_o} = C$ = constant, function (4) can be written in the form

$$\frac{F_m}{C} = \frac{B_o^2}{\lambda} e^{-\frac{4\pi}{\lambda} y} \tag{18}$$

The calculated curves in Fig. 2 show that separator No. 2 had a stronger magnetic attractive force on the drum surface but that it was decreased more rapidly by increasing distance y than the attractive force of separator No. 1.

In general, if two systems have the same field strength but different pole distances, the magnetic attractive forces of the systems differ. The system with the shorter pole distance has a stronger attractive force on the drum surface, but this force decreases more rapidly by increasing the distance from the drum surface.

An increasing force of magnetic attraction decreases the length of the magnetite stringers, c. f. Fig. 9, which should improve the separation (q. v. 11 below).

Resuts of the comparative tests of separators No. 1 and 2 are given in paragraph 14.

10. Effect of the peripheral speed of the drum

The function of the centrifugal force caused by the peripheral speed of the drum, c. f. function (10), can be written

$$\frac{F_{c_1}}{V} = 4\pi^2 s\, n^2 r \tag{19}$$

where n is the number of revolutions of the drum in a given time.

If the difference $\frac{F_m}{V} - \frac{F_{c_1}}{V}$ is considerable, the separation gives a good recovery. If this difference is minor in nature the concentrate grade is high.

In the case of $\frac{F_m}{V} = \frac{F_{c_1}}{V}$, we get the formula for the critical speed of the drum drum

$$n_c = \frac{1}{2\pi} \sqrt{\frac{1}{s\,r} \cdot \frac{F_m}{V}} \tag{20}$$

If the drum speed exceeds this critical point, magnetite will fly away from the separator shell.

Fe_3O_4 - grade and -recovery in separation tests of Otanmäki ore wi
with sepa

		Magnetite progresses in same dire													
Drum speed, r.p.m.	Field frequency, c.p.s.	180		130		100		90		86		75		63	
	Fe_3O_4, %	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.
60	Magnet wheel speed, r.p.m.	300		200				120				90		65	
	Rotation direction	opp. dir.		opp. dir.				opp. dir.				opp. dir.		opp. dir.	
	Concentrate 1	88.0	93.9	85.8	93.8			84.4	95.4					81.2	96.1
	" 2	91.0	92.4	89.3	92.7			86.8	91.2					86.5	94.5
	" 3	92.6	92.1	90.9	91.4			89.3	91.4					88.5	93.6
	" 4	93.5	91.3	91.5	90.9			90.8	91.4					89.4	94.3
	" 5	94.4	90.9	92.7	91.0			91.8	91.2					89.8	91.8
	" 6														
	" 7														
	" 8														
	" 9														
	" 10														
	Tailing	1.9	4.7	1.8	6.2			1.7	4.6					1.5	3.9
150	Magnet wheel speed, r.p.m.	210		110		50				22		0		24	
	Rotation direction	opp. dir.		opp. dir.		opp. dir.				opp. dir.				same dir.	
	Concentrate 1	88.5	53.6	88.5	65.5	85.1	71.7			85.6	72.9	85.1	82.5	84.4	84.0
	" 2	90.9	31.4	89.2	47.1	88.5	58.4			88.3	60.0	88.5	69.1	87.6	75.9
	" 3	92.7	16.7	90.0	39.5	90.0	47.2			89.7	51.1	89.0	59.6	88.1	68.3
	" 4			91.8	32.2	90.9	39.1			91.0	44.5	90.4	50.8	90.0	62.6
	" 5			92.6	26.9	92.2	33.3			91.8	39.5	91.8	47.5	90.9	57.7
	" 6														
	" 7														
	" 8														
	" 9														
	" 10														
	Tailing	18.3	46.4	11.8	34.5	8.3	28.3			8.8	27.1	4.6	17.5	5.8	16.0

Table 13.

mäki ore with several successive separations at different field frequencies. Tests were made w

with separator No. 1. Feed rate was 3 ton/h/ in first separation and 1 ton/h in the cleaner

gresses in same direction as drum																		
63		50		40		30		20		10		7		0		10		
Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Gr
65 opp. dir.		40 opp. dir.		20 opp. dir.		0		20 same dir.				46 same dir.		60 same dir.		80 same dir.		
81.2	96.1	80.5	96.7	76.5	96.7	72.8	97.6	62.5	97.4			43.5	95.9	34.1	99.0	48.9	97.6	61
86.5	94.5	86.8	96.1	82.8	94.1	80.5	96.9	71.9	96.1			55.3	94.8	45.0	98.4	60.1	97.3	68
88.5	93.6	87.7	93.9	85.1	92.9	81.5	94.9	75.0	94.9			61.0	97.2	49.7	97.8	64.2	97.0	71
89.4	94.3	89.3	93.7	86.2	92.0	83.5	94.7	78.7	96.1			63.3	96.0	53.3	98.4	66.9	96.8	7
89.8	91.8	90.5	93.3	87.5	91.7	85.2	94.8	79.3	94.5			64.6	94.7	55.5	98.0	67.8	95.4	7
				88.0	90.8	85.9	94.1	81.0	94.5			66.5	94.3	56.5	96.5	69.7	95.7	7
				89.2	91.1	86.3	93.7	81.2	93.1			67.8	93.7	57.7	95.3	71.6	96.3	78
								82.0	92.7			69.2	93.9	59.3	95.4	72.5	95.6	
								83.2	93.0			70.7	94.3	60.1	94.7	73.5	95.0	
								83.4	92.1			72.1	95.0	60.9	94.3	74.4	95.2	
1.5	3.9	1.5	3.3	1.4	3.3	1.3	2.4	1.2	2.6			1.3	4.1	1.4	1.0	0.8	2.4	(
24 same dir.		50 same dir.		70 same dir.		90 same dir.		110 same dir.		130 same dir.				150 same dir.		170 same dir.		
84.4	84.0	81.5	77.0	80.5	65.3	79.0	60.6	75.2	70.3	69.2	82.6			61.2	96.7	70.7	88.3	7
87.6	75.9	86.4	63.4	84.7	50.4	84.3	42.8	79.7	50.0	75.8	70.1			71.4	95.0	78.1	81.8	8
88.1	68.3	88.5	52.9	86.8	39.1	86.8	33.8	83.9	36.5	79.0	62.6			75.1	92.5	80.7	74.7	8
90.0	62.6	89.5	44.1	88.1	30.0	87.4	26.9	85.5	27.2	81.5	57.1			78.4	92.0	82.4	69.2	8
90.9	57.7	90.4	37.5	89.3	25.1	88.9	22.7	86.8	22.4	83.2	51.8			79.3	89.4	84.4	66.0	8
										84.2	46.7			80.3	87.9			
										85.1	42.0			81.8	87.0			
										85.5	38.3			82.1	85.0			
										85.9	35.2			82.8	83.4			
										86.8	32.5			83.1	81.8			
5.8	16.0	7.6	23.0	10.7	34.7	11.9	39.4	8.7	29.7	5.9	17.4			2.9	3.3	3.9	11.7	

made with samples with grinding fineness of 50 % minus 200 mesh, and
cleaner stages.

Magnetite progresses in opposite direction to drum										
0	20	30	40	50	65	75	90	110	130	180
Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.
0 e dir.	100 same dir.	140 same dir.	140 same dir.	160 same dir.	190 same dir.	210 same dir.	240 same dir.	280 same dir.	320 same dir.	420 same dir.
97.6	61.7 98.0	70.7 98.1	75.4 97.8	77.2 97.0	78.1 98.1	79.3 98.2	79.8 97.8	80.7 97.1	80.7 95.9	83.4 95.7
97.3	68.8 96.1	77.2 96.7	80.6 95.1	82.5 95.2	84.0 97.0	85.0 95.6	85.5 95.3	86.4 94.6	86.4 94.8	87.5 94.2
97.0	71.6 94.8	80.0 96.0	82.5 93.3	85.4 95.4	86.4 95.3	87.0 94.7	87.5 94.8	88.5 94.0	88.5 94.2	90.4 94.8
96.8	75.3 96.2	81.5 95.0	84.2 92.9	86.4 94.3	88.5 95.8	88.5 94.6	88.5 93.7	89.4 93.6	89.4 93.3	91.0 93.8
95.4	76.3 95.4	82.5 94.2	84.9 92.3	87.5 94.2	89.4 95.5	89.4 94.3	90.4 94.3	90.4 93.4	90.4 93.2	91.5 93.4
95.7	77.2 94.4	83.4 93.2								
96.3	78.9 94.7	84.4 93.4								
95.6										
95.0										
95.2										
2.4	0.8 2.0	0.6 1.9	1.1 2.2	11.1 3.0	1.1 1.9	1.1 1.8	1.1 2.2	1.1 2.9	1.1 4.1	1.3 4.3
70 e dir.	190 same dir.	210 same dir.	230 same dir.	250 same dir.	280 same dir.	300 same dir.	330 same dir.	370 same dir.	410 same dir.	510 same dir.
88.3	78.1 88.2	80.7 83.9	82.4 84.7	84.4 90.3	87.0 93.6	87.0 94.1	87.5 93.6	88.5 94.0	88.5 92.4	89.4 90.2
81.8	83.4 79.3	85.4 74.3	87.5 77.9	87.5 82.6	89.4 89.1	89.4 90.6	91.0 91.5	91.0 90.5	92.5 89.0	91.5 83.1
74.7	85.4 71.5	88.5 67.6	88.5 68.6	89.4 77.0	90.4 85.1	91.2 88.4	92.5 89.3	92.5 88.0	93.5 84.2	92.5 77.6
69.2	86.2 62.1	89.0 59.0	90.4 61.7	91.5 73.3	91.5 82.1	92.0 85.9	93.0 87.2	93.6 85.1	94.4 80.0	94.0 73.0
66.0	87.0 54.3	90.2 53.0	91.5 56.9	92.5 68.3	92.5 79.5	92.7 83.8	93.5 85.1	94.4 82.9	95.4 76.4	94.5 66.0
11.7	4.6 11.8	5.6 16.1	4.9 15.3	3.3 9.7	2.4 6.4	2.3 5.9	2.3 6.4	2.4 6.0	2.4 7.6	3.3 9.8

Drum speed, r.p.m.	
60	
180	

Fe_3O_4 - grade and -recovery in separation test
same as given in Ta

										Magnetite progresses in same direction as drum
Drum speed. r.p.m.	Field frequency, c.p.s	180	130	110	100	90	86	75	63	53
	Fe_3O_4, %	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.
60	Magnet wheel speed, r.p.m.	300	200	160		120			65	46
	Rotation direction	opp. dir.	opp. dir.	opp. dir.		opp. dir.			opp. dir.	opp. dir.
	Concentrate 1	82,3 95,7	81,3 98,2	81.3 99,1		76,6 96,6			75,1 98,0	72,8 97,6
	" 2	85,1 94,1	84.0 95,2	83,6 95,2		82,0 95,7			79,8 96,0	79.0 98.8
	" 3	86,8 93,5	86,4 95,4	85,9 95,4		83,6 94,4			81,2 94,6	80,9 95,9
	" 4	88,8 93,6	87,2 93,9	86,8 94,6		85,1 94,0			82.8 94.1	82,0 94,6
	" 5	90,9 94,6	89,2 94,1	88,5 95,1		87,3 95,5			84,3 94,0	83,6 94,6
	" 6									
	" 7									
	" 8									
	" 9									
	" 10									
	Tailing	1,6 4,3	1,5 1,8	1,5 0,9		1,5 3,4			1,5 2,0	1,4 2,4
150	Magnet wheel speed, r.p.m.	210	110		50		22	0	24	
	Rotation direction	opp. dir.	opp. dir.		opp. dir.		opp. dir.		same dir.	
	Concentrate 1	85,2 50,4	82.0 60,2		80,5 64,0		80,3 70,1	78,4 80,1	78,0 74,4	
	" 2	88,5 27,7	85,1 36,5		85,1 42,9		84,3 49,0	82,8 62,2	82,8 63,4	
	" 3	89,5 18,6	88,5 26,4		86,8 31,8		86,0 37,5	85,9 51,1	83,6 54,7	
	" 4		90,0 20,4		88,0 25,6		87,7 30,1	86,3 42,5	85,9 48,9	
	" 5				89,0 21,9		88,9 24,0	88,5 38,2	86,8 44,0	
	" 6									
	" 7									
	" 8									
	" 9									
	" 10									
	Tailing	13,7 49,6	11,7 39,8		10,4 36,0		9,3 29,9	6,9 19,9	8,7 25,6	

Table 14.

aration tests of Otanmäki ore with several successive separations at different field frequencies. Test consitions are th
iven in Table 13 except for the fineness of grinding, which was 70 % minus 200 mesh.

direction as drum								M			
53	50	40	30	20	10	7	0	10	20	30	40
Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.
46 opp. dir.		20 opp. dir.	0	20 same dir.		46 same dir.	60 same dir.	80 same dir.	100 same dir.	120 same dir.	140 same dir.
72.8 97.6 79.0 96.8 80.9 95.2 82.0 94.6 83.6 94.6 1.4 2.4		71.4 99.0 76.5 97.1 79.0 96.5 81.3 96.5 82.3 96.3 83.6 95.7 84.2 94.9 1.3 1.0	61.6 95.0 73.5 99.1 76.2 97.8 79.8 99.6 81.7 99.1 82.0 97.8 83.6 96.7 1.0 5.0	55.8 96.6 62.7 96.6 66.4 96.6 68.5 95.9 69.9 95.5 71.8 96.0 73.3 96.2 1.2 2.4		38.2 95.0 46.5 96.8 50.0 95.4 53.7 96.0 55.9 96.1 57.8 96.3 59.2 95.9 60.0 94.9 61.6 95.4 62.7 9n.5 1.3 5.0	30.7 95.5 39.5 96.9 42.5 93.8 46.0 94.6 48.0 94.5 50.0 94.8 51.1 94.1 52.1 93.3 53.7 94.0 55.3 95.2 2.3 4.5	41.6 96.7 53.3 97.3 56.3 94.6 59.3 95.0 61.7 95.5 62.6 94.7 64.2 95.1 0.9 3.3	53.3 97.1 60.9 94.5 64.3 93.6 67.8 95.3 69.8 95.9 1.0 2.9	62.8 97.1 70.7 96.9 73.5 96.5 76.3 97.6 77.3 96.9 1.1 2.9	67.5 97.9 76.3 97.7 77.3 95.7 78.6 94.9 80.4 95.5 1.1 2.1
	50 same dir.	70 same dir.	90 same dir.	110 same dir.	130 same dir.		150 same dir.	170 same dir.	190 same dir.	210 same dir.	230 same dir.
	75.2 67.4 80.5 52.6 84.0 41.4 85.2 33.3 86.0 27.4 10.3 32.6	72.8 54.6 79.8 41.4 82.8 31.9 83.6 24.5 85.9 20.1 13.8 45.4	72.2 46.5 79.0 31.5 81.3 25.1 83.5 18.5 17.2 53.5	65.7 41.7 72.2 26.5 76.6 20.3 17.7 58.3	60.4 59.1 67.8 43.0 72.0 33.7 73.5 27.7 78.7 23.6 13.4 40.9		50.0 87.9 61.8 88.5 65.0 85.3 68.5 84.8 69.9 83.0 70.8 81.1 71.8 79.5 72.6 78.0 73.5 77.0 74.8 76.4 5.2 12.1	61.7 78.1 69.6 71.8 72.5 65.8 75.4 60.2 77.8 55.3 8.6 21.9	67.9 69.7 74.4 57.4 77.2 47.9 78.6 41.0 79.8 35.2 11.1 30.3	70.7 81.0 76.3 66.6 78.8 55.0 80.6 46.7 81.5 39.2 7.4 19.0	73.5 86.4 78.9 74.7 81.5 66.8 82.3 59.6 83.1 51.9 5.3 13.6

ns are the

Magnetite progresses in opp. direction to drum															
40		50		65		75		90		110		130		180	
ade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.
140 ame dir.		160 same dir.		190 same dir.		210 same dir.		240 same dir.		280 same dir.		320 same dir.		420 same dir.	
.5	97.9	69.7	97.8	70.7	98.0	70.7	97.4	71.7	97.2	71.7	99.4	71.7	99.3	71.7	97.8
.3	97.7	77.2	97.0	79.0	98.0	79.8	97.6	80.6	97.2	81.5	97.4	83.4	98.4	82.5	95.4
.3	95.7	79.8	96.7	80.4	95.7	81.5	96.0	81.5	98.7	84.4	96.6	84.4	96.2	84.4	94.2
.6	94.9	81.5	96.1	82.4	95.8	83.4	95.9	83.4	94.7	85.4	96.2	85.4	95.5	86.4	93.2
.4	95.5	83.0	96.4	83.0	95.2	85.4	96.7	85.4	95.7	86.4	96.1	87.5	96.5	87.5	94.0
.1	2.1	1.1	2.2	1.0	2.0	0.9	2.6	1.0	1.8	1.0	0.6	0.9	0.7	1.2	2.2
230 ame dir.		250 same dir.		280 same dir.		300 same dir.		330 same dir.		370 same dir.		410 same dir.		510 same dir.	
.5	86.4	75.4	90.3	78.8	94.7	78.8	94.4	79.1	93.7	82.0	95.0	82.4	93.4	86.4	94.0
.9	74.7	80.6	82.9	82.4	90.1	82.4	90.8	84.4	92.6	86.4	92.7	85.4	88.5	88.5	87.3
.5	66.8	83.4	76.2	85.4	88.0	84.4	88.6	88.5	93.3	87.0	89.0	88.5	86.4	90.4	83.3
.3	59.6	85.4	70.0	86.7	85.2	86.4	87.4	89.0	90.9	88.2	86.7	89.4	83.2	90.7	78.5
.1	51.9	86.1	63.9	87.5	82.3	87.0	85.6	89.2	88.6	89.4	84.7	90.4	80.3	91.0	74.5
5.3	13.6	3.6	9.7	2.4	5.3	2.1	5.6	1.9	6.3	1.8	5.0	1.9	6.6	2.4	6.0

Drum speed, r.p.m.	Field f
	Fe_3O_4,
60	Magne Rotatio
	Concen
	Tailin
150	Magne Rotati
	Conce
	Tailin

Fe_3O_4 - grade and -recovery in separation tests of Otanmäki o

		Magnetite progresses in same direction as dru								
Drum speed,	Field frequency, c.p.s.	180	130	110	100	90	86	75	63	53
r.p.m.	Fe_3O_4, %	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Re
60	Magnet wheel speed, r.p.m.	300	200	160		120		90	65	46
	Rotation direction	opp. dir.	opp. dir.	opp. dir.		opp. dir.		opp. dir.	opp. dir.	opp. dir.
	Concentrate 1	63.8 93.7	62.0 94.7	61.6 97.6		57.7 94.7		56.4 95.2	54.2 95.2	51.6 94.
	" 2	69.2 92.5	68.4 94.9	67.2 95.8		63.6 92.9		63.3 93.7	62.5 95.4	60.4 93.
	" 3	71.0 91.6	70.6 94.5	67.9 93.4		67.0 92.8		66.5 94.0	65.7 95.3	64.3 94.
	" 4	72.8 92.0	71.4 93.3	69.2 93.2		68.4 92.7		67.8 93.6	67.7 94.6	65.8 92.
	" 5	74.0 92.2	72.1 93.2	71.4 94.7		70.5 94.1		69.0 93.5	68.1 93.2	68.5 94.
	" 6									
	" 7									
	" 8									
	" 9									
	" 10									
	Tailing	2.5 6.3	2.5 5.3	2.5 2.4		2.4 5.3		2.4 4.8	2.4 4.8	2.5 5.
150	Magnet wheel speed, r.p.m.	210	110		50		22	0	24	
	Rotation direction	opp. dir.	opp. dir.		opp. dir.		opp. dir.		same dir.	
	Concentrate 1	67.2 32.0	62.2 31.9		61.7 32.2		61.2 41.2	59.8 40.5	59.5 44.4	
	" 2	75.0 14.9	70.7 17.4		69.2 17.8		67.2 23.3	65.7 30.6	65.0 30.1	
	" 3		75.6 11.9		75.2 13.8		72.5 16.7	69.0 27.2	67.8 23.2	
	" 4							71.4 24.8	69.9 20.6	
	" 5							74.0 22.4	71.4 17.9	
	" 6									
	" 7									
	" 8									
	" 9									
	" 10									
	Tailing	17.8 68.0	17.2 68.1		17.0 67.8		16.5 58.8	16.2 59.5	15.8 55.6	

Table 15.

tanmäki ore with several successive separations at different field frequencies. Test conditions are the same as g.ven for the fineness of grinding, wh.ch was 90 % minus 200 mesh.

direction as drum												M
	63	50	40	30	20	10	7	0	10	20	30	40
c.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.	Grade Rec.
	46 opp. dir.		20 opp. dir.	0	20 same dir.		46 same dir.	60 same dir.	80 same dir.	100 same dir.	120 same dir.	140 same dir.
.2	51.6 94.8		46.5 95.1	41.5 93.8	35.8 94.8		25.4 92.7	23.3 94.4	28.6 96.5	32.7 96.7	37.3 94.5	41.6 97.5
.4	60.4 93.7		55.8 94.5	48.5 92.2	43.5 94.8		27.8 91.3	23.8 92.5	31.4 94.4	39.8 94.0	47.1 93.7	53.3 98.4
.3	64.3 94.0		61.0 96.0	54.0 91.9	46.5 91.9		29.7 90.3	24.2 90.6	35.3 93.2	43.5 91.6	53.0 95.2	57.7 96.1
.6	65.8 92.7		63.8 95.8	57.5 91.7	50.0 92.7		31.6 90.3	25.3 92.0	38.6 93.1	47.2 92.3	56.2 94.7	60.1 95.3
.2	68.5 94.2		64.3 93.7	59.2 90.7	52.8 93.2		33.4 90.5	26.0 91.8	41.0 93.0	51.0 93.8	57.7 93.5	61.7 94.6
			66.4 94.5	61.5 91.1	53.9 91.5		34.0 87.7	26.8 91.8	42.9 92.4	53.3 93.6	59.3 93.5	
			67.7 94.3	63.0 90.7	56.9 93.0		35.8 88.4	27.2 90.6	44.5 91.1	54.3 91.7	60.1 92.3	
.8	2.5 5.2		2.5 4.9	2.9 6.2	3.0 5.2		4.0 7.3	5.2 5.6	3.9 3.5	3.3 3.3	2.7 5.5	2.4 2.5
.		50 same dir.	70 same dir.	90 same dir.	110 same dir.	130 sam. dir.		150 same dir.	170 same dir.	190 same dir.	210 same dir.	230 same dir.
.4		55.8 30.3	54.8 21.7	52.4 15.6	48.0 11.3	43.5 13.3		36.4 58.0	44.2 8.2	49.2 24.6	52.4 42.8	53.3 56.0
.1		62.7 19.7	62.0 12.8	60.0 8.1	57.5 5.7	52.5 7.6		45.5 53.7	53.3 5.1	55.5 16.4	58.0 29.7	59.3 45.6
.2		67.8 15.5	66.5 9.6					50.0 50.2		59.3 13.1	61.7 23.7	62.6 35.6
.6		70.7 12.6						52.7 49.4				65.1 30.2
.9								53.7 47.7				
								55.0 47.0				
								56.8 46.8				
.6		17.6 69.7	19.1 78.3	19.2 84.4	19.6 88.7	20.7 86.7		14.4 42.0	22.2 91.8	21.6 75.4	15.0 57.2	13.9 44.0

as g.ven in Table 13 exept

Magnetite progresses in opposite direction to drum															
40		50		65		75		90		110		130		180	
rade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.	Grade	Rec.
140 same dir.		160 same dir.		190 same dir.		210 same dir.		240 same dir.		280 same dir.		320 same dir.		420 same dir.	
1.6	97.5	41.0	94.5	41.6	95.6	42.0	94.2	41.0	95.3	40.4	96.7	39.2	97.2	39.2	96.1
3.3	98.4	54.7	95.7	55.5	96.2	56.2	96.5	54.7	95.3	55.5	97.1	54.8	97.1	54.8	97.5
7.7	96.1	60.1	94.7	61.7	97.0	61.7	95.6	61.7	96.6	61.7	95.4	62.6	96.8	62.6	96.7
0.1	95.3	62.5	94.2	64.2	96.7	64.2	94.9	66.0	97.8	66.0	96.8	67.9	98.2	67.9	98.2
1.7	94.6	64.0	94.4	64.8	94.9	66.0	95.0	67.3	97.3	68.8	98.1	69.7	97.2	69.7	96.4
2.4	2.5	2.4	5.1	2.3	4.4	2.3	5.8	2.2	4.6	1.9	3.3	2.0	2.8	2.0	3.9
230 same dir.		250 same dir.		280 same dir.		300 same dir.		330 same dir.		370 same dir.		410 same dir.		510 same dir.	
3.3	56.0	55.3	69.2	57.0	79.8	57.7	85.7	58.5	90.2	57.7	89.6	59.3	91.8	60.9	92.4
9.3	45.6	61.7	64.4	63.0	77.3	64.2	83.6	65.0	87.5	66.0	90.1	66.9	91.0	70.7	93.9
2.6	35.6	64.2	59.0	67.0	77.1	66.9	82.0	68.0	86.8	69.7	90.3	69.8	90.8	72.2	91.3
5.1	30.2	66.8	55.9	68.5	75.1	69.7	82.1	69.8	85.3	70.7	88.7	71.6	90.7	74.0	90.1
		67.9	51.2	70.1	74.3	70.7	80.5	71.5	84.8	71.6	87.7	72.5	89.8	75.4	88.5
13.9	44.0	11.6	30.8	8.4	20.2	6.1	14.3	4.4	9.8	3.6	10.4	3.1	8.2	2.8	7.6

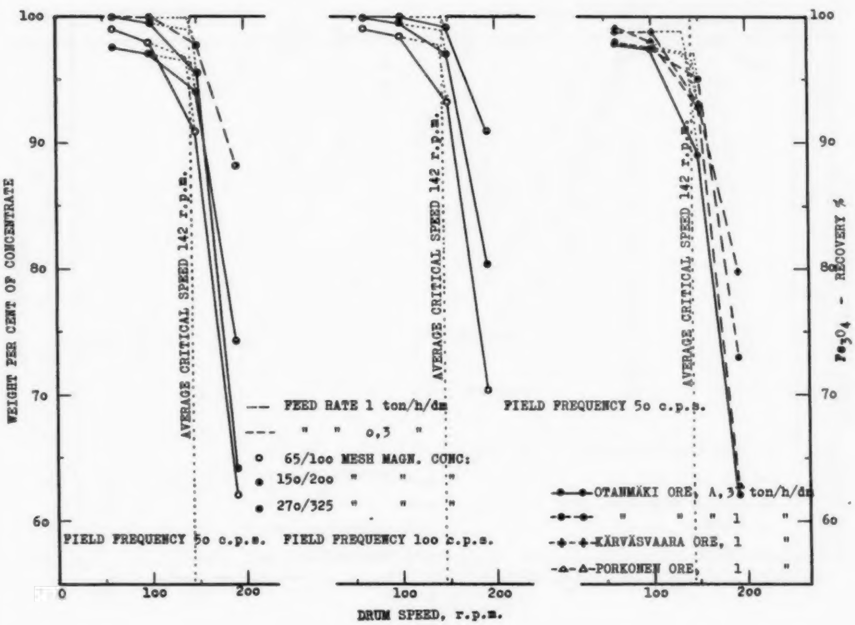


Fig. 11. Experimental determination of critical speed of separator No. 1 at field frequencies of 50 and 100 c.p.s. with sized magnetite concentrate of Kärväsvaara and with unscreened samples of Otanmäki, Kärväsvaara and Porkonen ores when magnetite progresses in same direction as drum.

The critical speed of separators Nos. 1 and 2 was determined experimentally by separating samples of different ores and of screened magnetite concentrate at various speeds. The effect of feed rate and field frequency on critical speed was also tested. The magnetite recovery indicated how magnetite is held on the drum surface.

From the results given in Figures 11 and 12, the following conclusions can be drawn:

- The critical speed of separator No. 1 is 142 $\pm$ 3 r.p.m. at field frequencies of both 50 and 100 c.p.s. It depends to only a minor degree on the feed rate and/or grain size. Samples of ores and magnetite concentrate gave similar results.
- The critical speed of separator No. 2 decreases with increasing fineness of grinding and increasing feed rate of magnetite.

The terms F_m/V and s of function (20) vary with different materials and feed rates. The volume concentration is low when separating ores at high feed rate, and/or fine grinding. Thus the corresponding critical speeds are low.

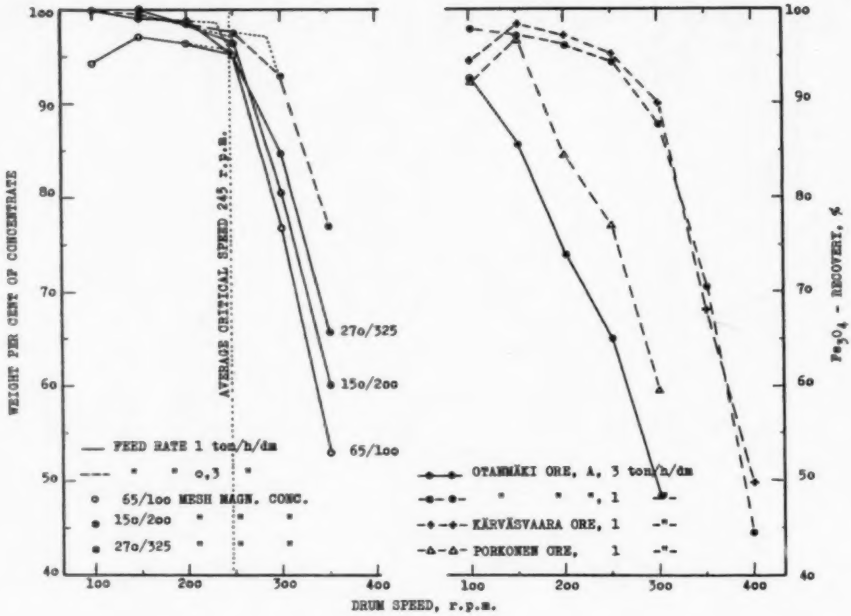


Fig. 12. Experimental determination of critical speed of separator No. 2 with sized magnetite concentrate of Kärväsvaara and with unscreened samples of Otanmäki, Kärväsvaara and Porkonen ores. Magnetite progresses in same direction as drum.

The effect of feed rate and of grinding fineness on critical speed is more pronounced with separator No. 2 because its magnetic attractive force decreases with increasing distance from the drum surface much more rapidly than that of separator No. 1. According to Fig. 2, the magnetic attractive forces of separators Nos. 1 and 2 were equal at a distance of 1.4 mm from the drum surface. The measured length of magnetite clusters at 100 c.p.s. was about 2.5 mm. Because the clusters rotate about their centres of gravity above the shell the cloud of magnetite clusters must be several millimetres thick. At such distances from the drum surface the magnetic attractive force of separator No. 2 was much weaker than that of separator No. 1. Thus the calculated values given in Fig. 2 seem to be in agreement with the results of the tests designed to determine the critical speeds.

When the drum speed is below the critical value the concentrate grade increases in nearly direct proportion to the drum speed. (If the critical speed is exceeded, the grade of the concentrate decreases as shown by the results at 200 r. p. m. in Table 10.)

An increasing number of drum revolutions increases the peripheral speed. Thus the feed rate can be increased without increasing the thickness of material on the

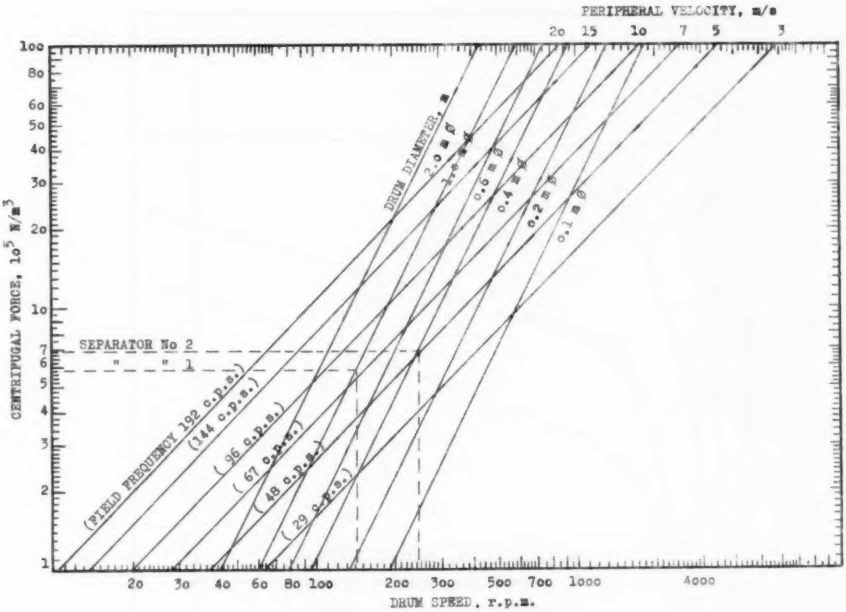


Fig. 13. Diagram of the relations between the centrifugal force and the number of rotations, peripheral velocity and diameter of drum (the value of s is 5000 kg/m^3 in the calculations). The given values of field frequencies are valid if the magnet-carrying wheel does not rotate and the pole distance is 52 mm.

drum surface. Table 10 shows that a feed rate of 5 ton/h/dm at a drum speed 150 r.p.m. gave in general a better concentrate grade than a feed rate of 1 ton/h/dm at 100 r.p.m.

An increasing drum speed decreases the magnetite recovery, but the effect is slight at speeds below the critical.

From function (20), it is apparent, that the speed of rotation of the drum can be increased if the magnitude of magnetic field is increased. With increasing speed, the centrifugal force, the capacity of the separator and the frequency of the rotating magnetic field are increased.

Function (20) further illustrates that with a constant attractive force an increase in diameter decreases the critical speed. Irrespective of the decrease of critical speed the peripheral velocity increases

$$v = 2\pi rn = \sqrt{\frac{r}{s} \cdot \frac{F_m}{V}} \qquad (21)$$

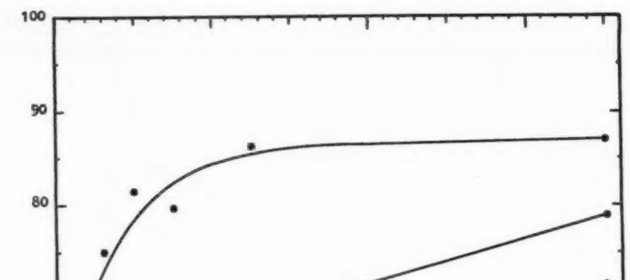


Fig. 14. Effect of field frequency on Fe_3O_4-grade with different grinding finenesses of Otanmäki ore. The curves are drawn up according to the values given in Tables 10-12, drum speed 60 r.p.m., feed rate 1 ton/h/dm and magnetite progressing in same direction as the drum.

An increase in peripheral velocity again increases the capacity and field frequency.

Figure 13 shows a diagram of the relationship between the centrifugal force and the number of revolutions, the peripheral speed and the diameter of the drum. If the magnet wheel is stationary, the curves of peripheral velocity also indicate field frequency. The observed critical speeds and the corresponding centrifugal forces of separators Nos. 1 and 2 are also marked on the diagram.

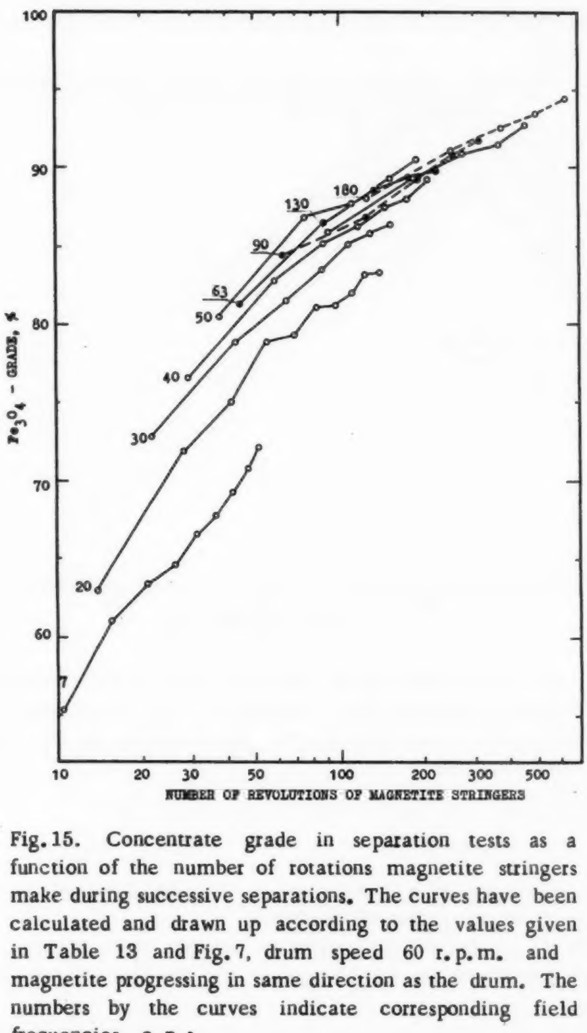


Fig. 15. Concentrate grade in separation tests as a function of the number of rotations magnetite stringers make during successive separations. The curves have been calculated and drawn up according to the values given in Table 13 and Fig. 7, drum speed 60 r.p.m. and magnetite progressing in same direction as the drum. The numbers by the curves indicate corresponding field frequencies, c.p.s.

11. Effect of the speed of rotation and direction of the magnet wheel

On a separator shell, magnetite powder makes tumbling movements caused by the rotating field. If the magnet wheel and the drum rotate in the same direction in such a fashion that the wheel runs at a higher speed, the tumbling movement is opposite to the direction of the shell. This movement will be in the same direction

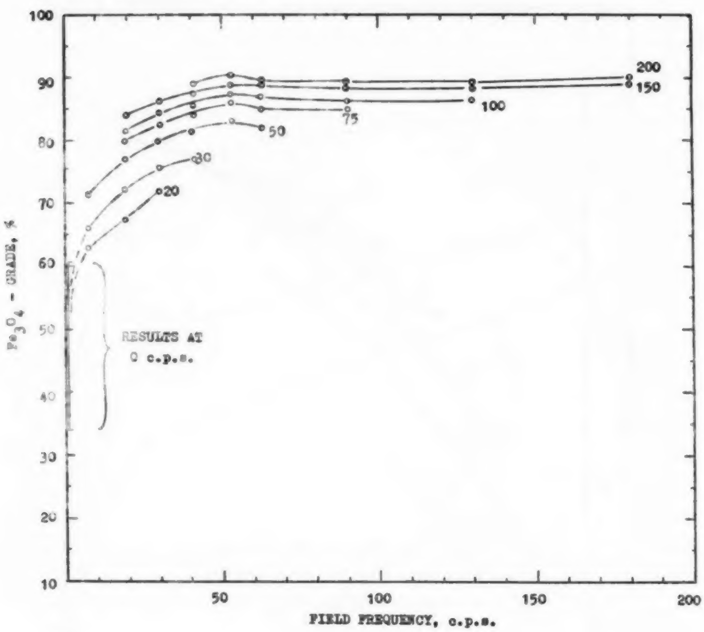


Fig. 16. Concentrate grade obtained after a fixed number of revolutions at different field frequencies. The curves have been drawn up by means of Fig. 15. The numbers by the curves indicate rotations.

if the magnet wheel runs at a lower speed in the same direction, or at any speed in the opposite direction to that of the drum.

The number of the revolutions magnetite stringers make between feeding and disharge points depends on the field frequency and the time magnetite remains on the shell.

Fig. 14 shows the effect of field frequency on concentrate grade in rougher separations. A number of similar curves can be drawn from the data given in Tables 10-12. The increase of concentrate grade is almost directly proportional to the field frequency at values 0-50 c.p.s. At higher field frequencies, the grade/frequency curves become more or less horizontal.

The shape of the curves can be explained if every cycle causing a revolution of magnetite stringers is considered as a unit separation. From visual observations, we know that if there is enough material on the separator shell, every revolution causes a rearrangement of the grains and every rearrangement gives the locked non-magnetic particles an opportunity to escape from the stringers.

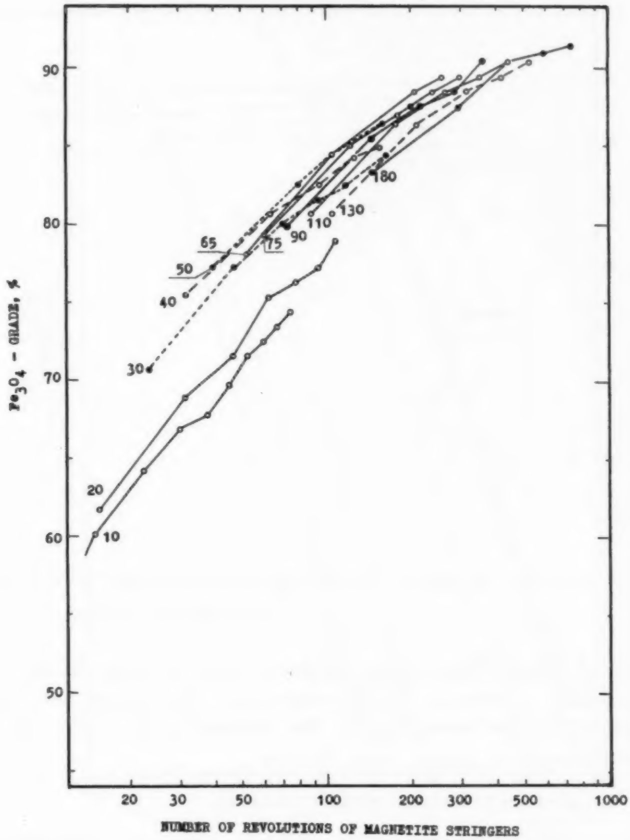


Fig. 17. Concentrate grade in separation tests as a function of the number of rotations magnetite stringers make during successive separations. The curves have been calculated and drawn up according to the values given in Table 13 and Fig. 7, drum speed 60 r.p.m. and magnetite progressing in opposite direction to the drum. The numbers by the curves indicate corresponding field frequencies, c.p.s.

The effectiveness of the unit separations is high at the beginning of the separation process, but weakens when the separation is continued. In his approach to the theory of magnetic concentration, LAURILA[15] stated that the escape probability of the non-magnetic particles depends on the number of the unit processes in the previous part of the concentration. Due to magnetic flocculation, the escape of

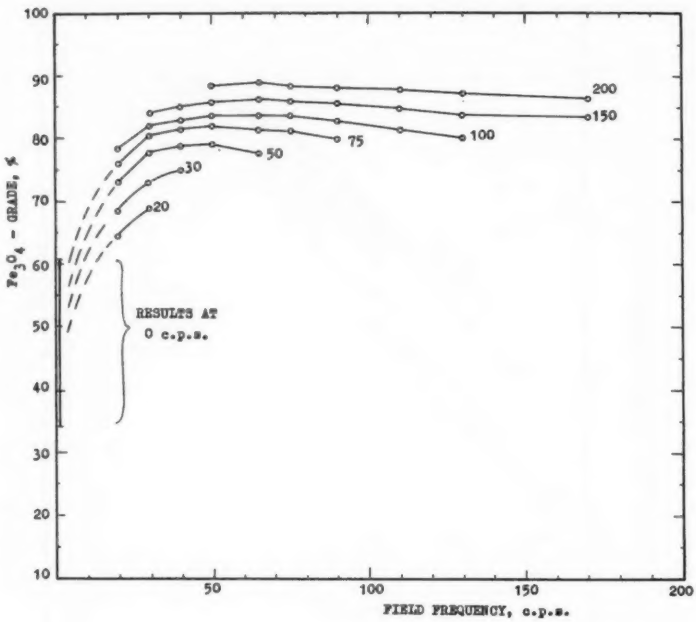


Fig. 18. Concentrate grate obtained after a fixed number of rotations at different field frequencies. The curves have been prepared on the basis of Fig. 17. The numbers by the curves indicate rotations.

non-magnetic particles becomes more difficult when the concentration of the magnetic component in the powder increases.

The effectiveness of the unit separations depends not only on the number of the previous unit processes, but also on the field frequency at which the unit separations have been carried out.

In Fig. 15 are plotted the concentrate grades of a number of tests against the number of revolutions made by magnetite material. The number of revolutions was calculated by taking into consideration the speed of progression of magnetite as given in Fig. 7. Each test was made at a different field frequency and contained several successive separations. The feed rate of magnetite was constant in each separation.

Fig. 16, which was prepared on the basis of Fig. 15, gives the concentrate grades after a fixed number of revolutions at different field frequncies. The "cleaning effectiveness" of the unit separations increased with increasing field frequency until 50 c. p. s. and at higher field frequencies remained constant or decreased slightly.

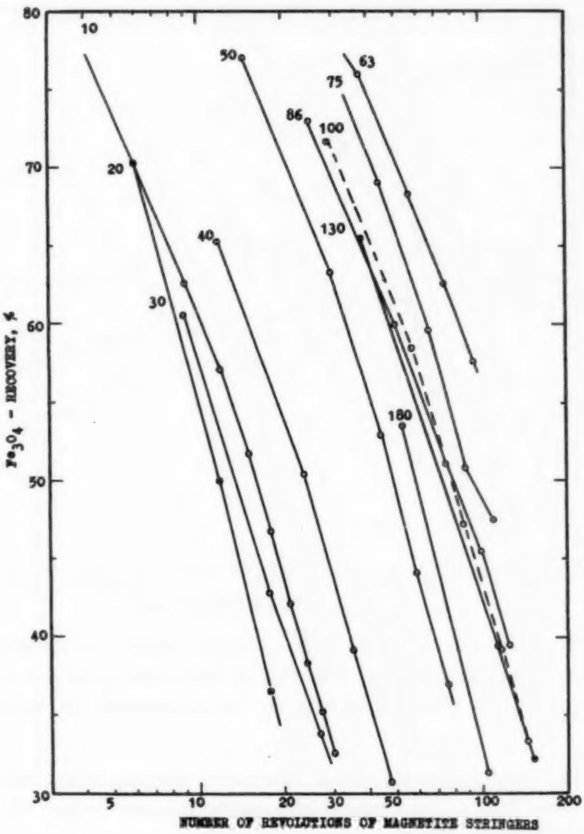


Fig. 19. Recovery in separation tests as a function of the number of rotations magnetite stringers make during successive separations. The curves have been calculated and drawn up according to the values given in Table 13 and Fig. 7, drum speed 150 r.p.m. and magnetite progressing in same direction as the drum. The numbers by the curves indicate corresponding field frequencies, c.p.s.

This phenomenon was independent of the direction of the progression of the stringers, c.f. Figs. 17 and 18, and grinding fineness, c.f. Fig. 23, and can be explained by observation of the films:

a) The stringers are shorter at higher field frequencies, which means that more clusters (more rearrangements) are formed from the same amount of magnetite.

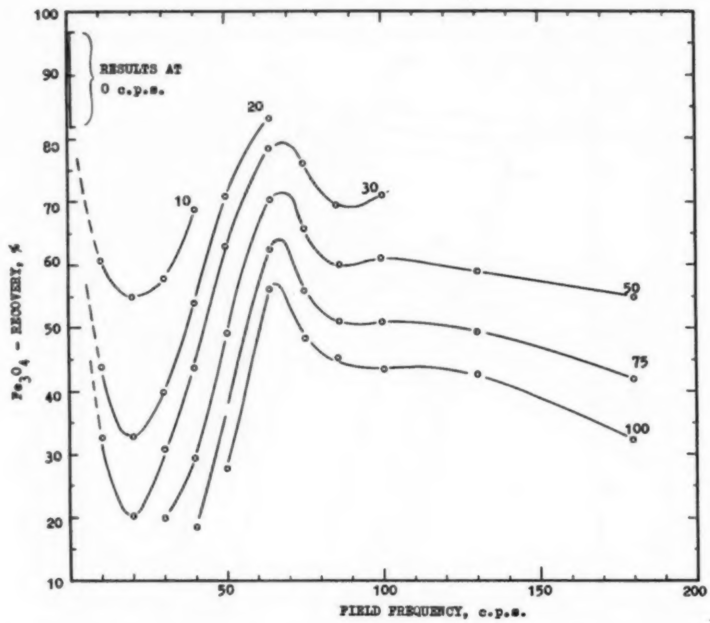


Fig. 20. Recovery obtained after a fixed number of rotations at different field frequencies. The curves have been prepared on the basis of Fig. 19. The numbers by the curves indicate the rotations.

An increasing field frequency should therefore increase the effectiveness of separation until 100 c.p.s.; above this frequency the length of the stringers decreases slowly, c.f. Fig. 8.

b) The rotations the stringers make in contact with the shell probably rearrange the grains more effectively than the rotations in the air. The clusters begin to jump from the drum surface at frequencies over 50 c.p.s.; thus the cleaning effectiveness of the unit separations is decresed at field frequencies over 50 c.p.s.

The combined effect of these two factors is probably the reason for the shape of the curves in Figures 16, 18 and 23.

In the separation tests illustrated in Figures 15-18, the conditions were such that the recovery was high, over 91 %. Another series of separation tests with a higher drum speed was made in order to investigate the effect of field frequency on the recovery. When the drum speed was increased, the difference between magnetic attractive and centrifugal forces dropped and the variations in the recovery were more pronounced.

Fig. 19 shows the recovery as a function of the number of rotations when the stringers progress in the same direction as the drum, and Fig. 20 the same recoveries after a fixed number of rotations at different field frequencies.

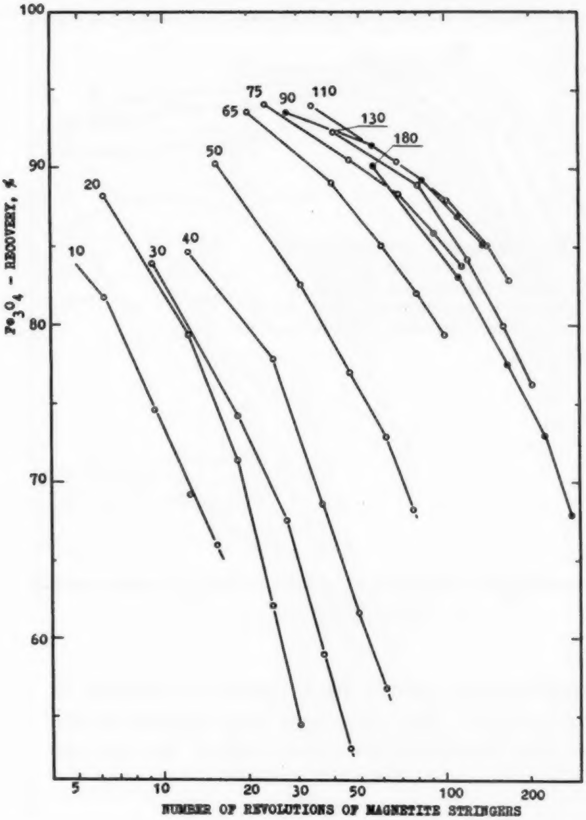


Fig. 21. Recovery in separation tests as a function of the number of rotations magnetite stringers make during successive separations. The curves have been calculated and drawn up according to the values given in Table 13 and Fig. 7, drum speed 150 r.p.m. and magnetite progressing in opposite drection to the drum. The numbers by the curves indicate corresponding field frequencies, c.p.s.

The recovery of the unit separations had a minimum at a field frequency of 10-30 c.p.s. and a clear maximum at a frequency of 65-70 c.p.s.

If the stringers were progressing in the opposite direction to the drum, there was again a minimum at low frequencies, 10-20 c.p.s., but the recovery reached its maximum value at 100 c.p.s. and was decreased only slowly at higher field frequencies, c.f. Figures 21 and 22.

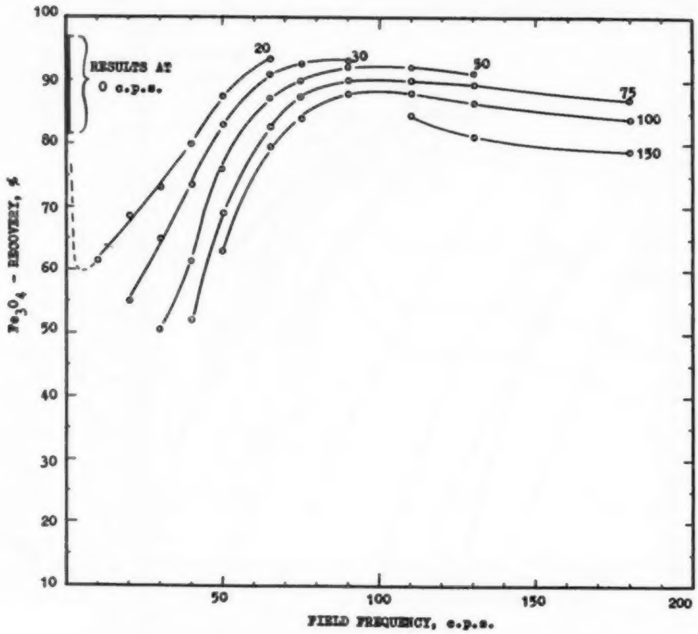


Fig. 22. Recovery obtained after a fixed number of rotations at different field frequencies. The curves have been prepared on the basis of Fig. 21. The numbers by the curves indicate the rotations.

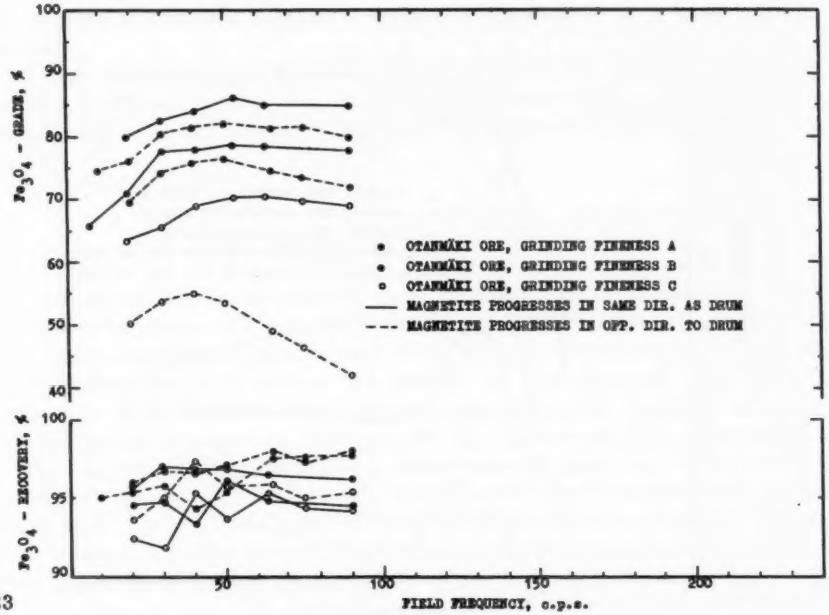
Fig. 23. Concentrate grade and recovery obtained after 75 rotations at different field frequencies in separation tests of Otanmäki A, B and C ores. The curves have been drawn up according to the values given in Tables 13-15, drum speed 60 r.p.m.

Fig. 24. Concentrate grade obtained after 75 rotations at different field frequencies in separation tests of Otanmäki A, B and C ores. The curves have been drawn up according to the values given in Tables 13-15, drum speed 150 r.p.m.

Similar results were obtained with all three grinding finenesses of Otanmäki ore, c.f. Fig. 25.

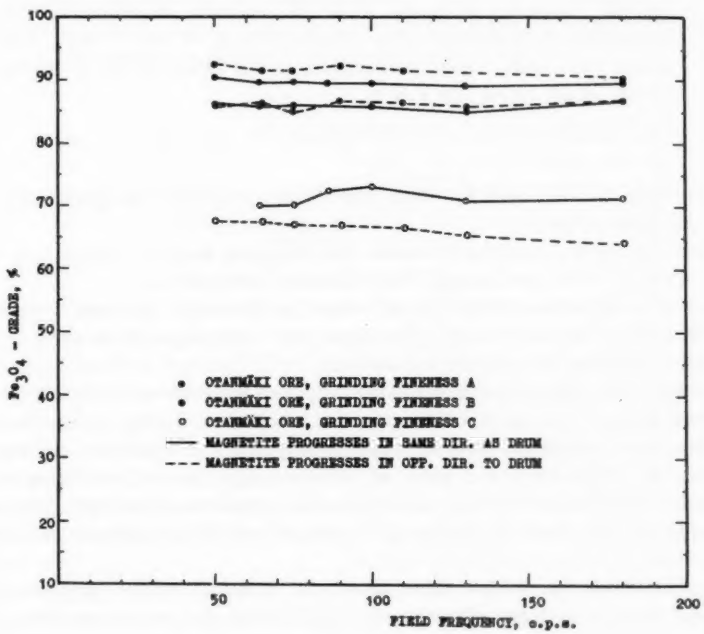
This is probably explained as follows:

At low frequencies, the stringers are long. The combined centrifugal force caused by the peripheral speed of the drum and by the rotations of the stringers,



Fe3O4 - GRADE, %
Fe3O4 - RECOVERY, %
OTANMÄKI ORE, GRINDING FINENESS A
OTANMÄKI ORE, GRINDING FINENESS B
OTANMÄKI ORE, GRINDING FINENESS C
MAGNETITE PROGRESSES IN SAME DIR. AS DRUM
MAGNETITE PROGRESSES IN OPP. DIR. TO DRUM
FIELD FREQUENCY, c.p.s.

23



Fe3O4 - GRADE, %
OTANMÄKI ORE, GRINDING FINENESS A
OTANMÄKI ORE, GRINDING FINENESS B
OTANMÄKI ORE, GRINDING FINENESS C
MAGNETITE PROGRESSES IN SAME DIR. AS DRUM
MAGNETITE PROGRESSES IN OPP. DIR. TO DRUM
FIELD FREQUENCY, c.p.s.

24

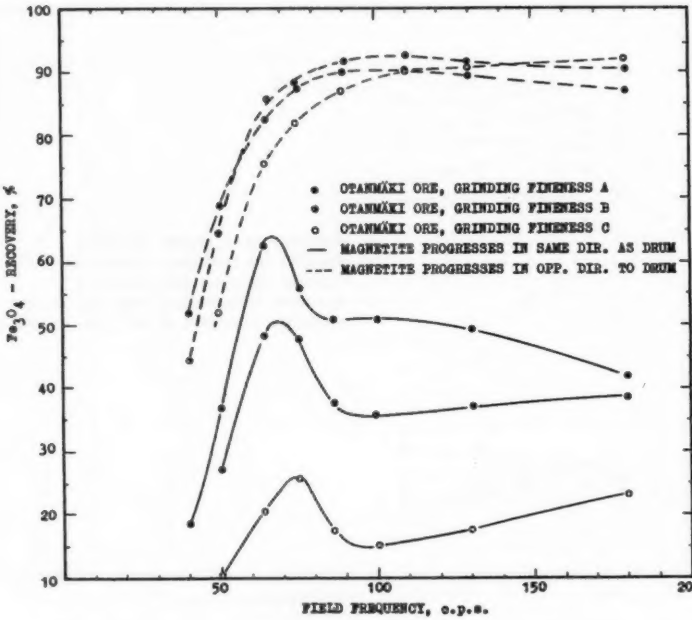


Fig. 25. Recovery obtained after 75 rotations at different field frequencies in separation tests of Otanmäki A, B and C ores. The curves have been drawn up according to the values given in Tables 13-15, drum speed 150 r. p. m.

c.f. function 10, may cast off those parts of the magnetite stringers which are far from the drum surface.

When the field frequency increases the stringers become shorter and are less easily removed from the stronger field near the drum surface.

The centrifugal force caused by the rotations of stringers increases with increasing field frequency. At high field frequencies this centrifugal force is so strong that magnetite particles or stringers are cast off.

A third centrifugal force is occasioned by the progression of the stringers along the drum surface. The speed of this progression is low, c.f. Fig. 7, and accordingly the calculated centrifugal force is small. In any case, in separation conditions near the critical drum speed the direction of the progression of the stringers has an apparent effect. It can increase or decrease the combined centrifugal forces. Thus the shape of the recovery curves in Figures 20 and 22 is different at high field frequencies.

Fig. 23 shows that at low drum speed the direction of the progression of the stringers has only a slight effect on the recovery of the unit separations, but that

the cleaning effectiveness is higher if the stringers progress in the same direction as the drum.

At high drum speeds, the direction of the progression has a slight effect on the cleaning effectiveness, c.f. Fig. 24, but the recovery of the unit separations is much higher when the stringers progress in the opposite direction to the drum, c.f. Fig. 25.

12. Effect of the feed rate

It has already been stated that there must be enough material on the drum surface for the rearrangement of the grains in the stringers. Fig. 26 shows the effect of the feed rate on concentrate grade. If the feed rate of Otanmäki A ore is less than 0.2 ton/h/dm, there is a drop in the number of rearrangements and thus the concentrate grade decreases. When the feed rate exceeds the optimum point, the rotations of the stringers are hindered and the concentrate grade again decreases.

The fact that high feed rates give a poor concentrate grade but a good recovery at low drum speeds, c.f. Tables 10-12, indicates that a thick magnetite bed deforms the rotating field[13], and the movement of magnetic clusters is hindered. At high drum speeds, a high feed rate does not increase the recovery, because the centrifugal force throws the magnetite away from the magnetic field.

The effect of feed rate depends on the amount of magnetite in the feed. Therefore the feed rate should be calculated as tons per hour of magnetite. If this is not taken into consideration, and the feed rate of magnetite is different in first separation and cleaner stages, there is a bend in the curve representing the grade as a function of successive separation (or number of rotations).

13. Effect of different magnetite materials

The materials to be separated differ from each other

- in magnetite content
- in the nature of silicate minerals
- in the fineness of grinding.

All these variables effect the effective permeability μ_a of the clusters. The effective permeability, and thus the magnetic attractive force, seem to rise if the volume concentration of magnetite is increased, if the dust of silicate minerals does not adhere to the surface of magnetite grains, and if the grain size is increased.

Table 7 shows that even if the length of the clusters drops according to decrease in grain size, the number of grains in a cluster is increased. Thus the probability that non-magnetic particles will escape is less. This is one reason for the decreasing concentrate grade by decreasing grain size, c.f. Fig. 23. Another important reason is the effect of adhesive and cohesive forces which act between the particles of very fine size.

It is actually the finest of dust, with a grain size of only a few microns, which is deleterious in the dry separation. The dust of some gangue minerals adheres so

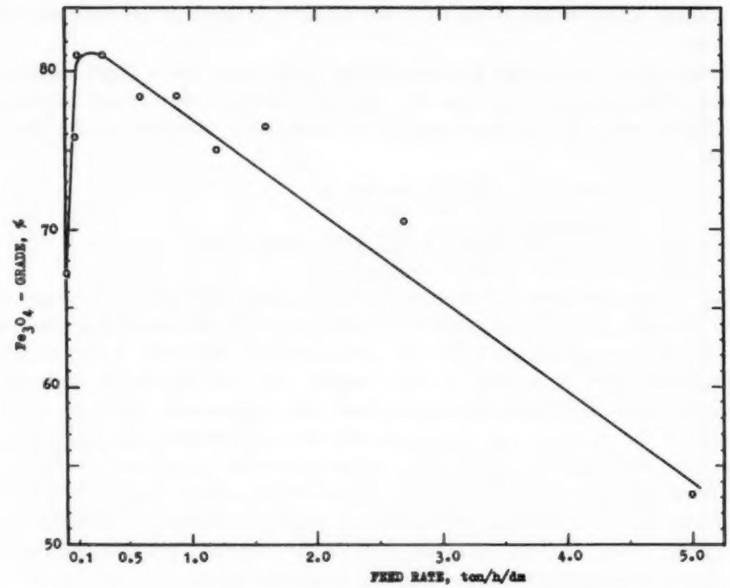


Fig. 26. Effect of feed rate on Fe_3O_4-grade in separation tests of Otanmäki A ore, drum speed 60 r.p.m., field frequency 30 c.p.s. and magnetite progressing in the same direction as the drum. In all tests the recovery was over 96.6 per cent.

firmly to the surface of magnetite grains that it follows the magnetite into the concentrate, thereby decreasing its grade. The addition of a small quantity of fatty acids to a grinding or drying unit helps in dispersing the material[19]. CAVANAGH[12] proposed that the fine material should be suspended in air and fed as an airborne stream on to the separator.

As an example of the effect of the nature of gangue minerals, Table 16 presents the results of dry separations of Otanmäki and Raajärvi ores. The ores were equal in grinding fineness, 50 % minus 200 mesh, and their magnetite minerals had the same Fe-content, about 70 %. Although Raajärvi ore contains more magnetite, it is more difficult to dry separate than Otanmäki ore, because the gangue minerals, dolomite and serpentine, smear the magnetite grains more than do the gangue minerals in Otanmäki ore. As regards gangue minerals, each ore is individual and must be tested separately.

The moisture content of ores intensifies the adherence of silicate dust to magnetite grains. The moisture should be below 1 % H_2O, and with fine grinding below 0.2 % [10, 19].

If the fine dust is eliminated, separation of the coarse part can be performed without difficulty. A dry gringing and air classification test of Otanmäki ore gave

Table 16.

Result of dry separation of Otanmäki and Raajärvi ores using separator No. 1, drum speed 100 r.p.m., magnet wheel stationary. Fineness of grinding of both ores about 50 % under 200 mesh.

Product	OTANMÄKI	RAAJÄRVI
	Fe, %	Fe, %
Feed	37.7	47.1
Concentrate grade after one separation	64.3	64.7
Concentrate grade after three separations	66.2	66.0

Table 17.

Screen analyses, specific surface and dry separation results of three different products obtained from an Aerofall Mill grinding of Otanmäki ore.

	Classifier product	Cyclone product	Multiclone product
Grain size, Tyler mesh			
+ 20	0,9		
- 65	39,8	95,3	
- 200	5,0	67,9	
- 400			100,0
Specific surface, cm^2/cm^3	470	3020	29200
Weight, per cent	65,4	32,3	1,7
Dry magnetic concentrate after three separations			
Fe_3O_4, per cent	91,3	94,8	34,4
Fe -"-	67,9	68,0	36,2
TiO_2 -"-	2,5	2,0	7,9
SiO_2 -"-	1,0	2,6	
Recovery -"-	85,0	89,2	2,9

three products of different grain size: classifier-, cyclone-, and multiclone-product. Each of these materials was separated three times using separator No. 1.

Table 17 gives the findings. The concentrates of the classifier and cyclone products were excellent; no separation was obtained with multiclone dust. The multiclone dust had such a high specific surface, 29200 cm^2/cm^3, that the adhesive forces acting between the particles dominated in the separation.

14. Comparative separation tests

As separators equipped with permanent magnets do not readily allow variation of the field, comparative tests with different magnetic attractive forces were not made. Although separators Nos. 1 and 2 produced different forces of attraction, they also had a different pole distance and drum diameter.

For a comparison of separators Nos. 1 and 2 the follovwing condition should exist:

- equal drum speeds as a pecentage of the critical speed
- equal field frequencies
- the same direction of progression of magnetite clusters
- feed rates in the same relation as the peripheral velocities of the drums.

Table 18 presents such comparative tests with Otanmäki A ore. The results show that separator No. 1 gives a better grade as well as a better recovery than separator No. 2. The effect of feed rate on the results is slight with separator No. 1 but substantial with separator No. 2.

The difference in concentrate grade can be explained by the difference in the number of rotations, 112 and 67, made by the magnetite stringers during five successive separations with separators Nos. 1 and 2 respectively. The difference in recovery depended on the difference in pole distance, which affected the gradient of the magnetic field and the magnetic attractive force, c.f. Fig. 2. Separator No. 1, with a pole distance of 52 mm, gave better results than separator No. 2 with a pole distance of 36 mm.

Fig. 27 presents the grade/recovery curves of four tests, each of 6 separations with separator No. 1. The tests were made under different conditions, as illustrated in Fig. 27. From the results, the following conclusions can be drawn:

- The higher drum speed, 100 r.p.m., gives a better concentrate grade than the lower speed, 60 r.p.m.
- The high field frequencies, 112-127 c.p.s., give a better concentrate grade than low frequencies, 31-51 c.p.s.
- The magnetite recovery is grater in tests 2 and 4, where the direction of magnetite motion was opposite to that of drum, than in tests 1 and 3, where magnetite progressed in the same direction as the drum.
- Test 2 (low drum speed, high frequency) gave the best overall results, bearing in mind both concentrate grade and recovery. The grade of the rougher concentrate was already an improvement on the concentrate of test 1 after six separations.

These results are in agreement with those given in Tables 10-15. The experimental conditions in tests 2 and 4 were apparently near the optimum. When

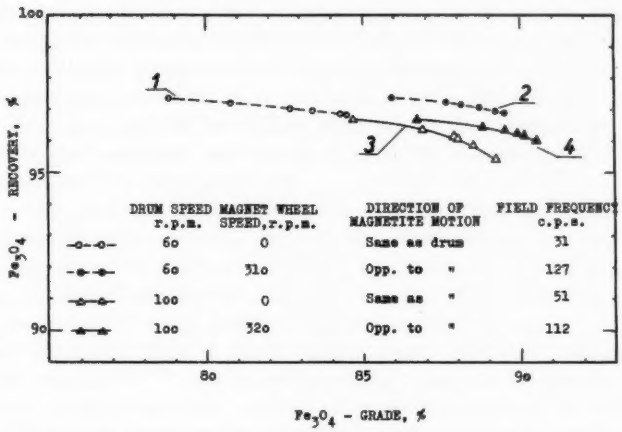


Fig. 27. Effect of successive separations of Otanmäki A ore on Fe_3O_4-grade and recovery. Separator No. 1 was fed at a rate of 1 ton/h/dm in the first separation, and 0,5 ton/h/dm in the five succeeding separations.

Table 18.

Separation tests of Otanmäki ore using separator No. 1 (drum diameter 1 m, pole distance 52 mm, speed 120 r.p.m. = 85 % of critical, magnet wheel stationary, field frequency 60 c.p.s.) and separator No. 2 (drum diameter 0.4 m, pole distance 35 mm, speed 204 r.p.m. = 84 % of critical, magnet wheel stationary, field frequency 61 c.p.s.).

Feed rate, ton/h	Separator No. 1				Separator No. 2			
First separation	4.4		1.46		3.0		1.0	
Cleaner stages	1.46		0.5		1.0		0.33	
	Fe_3O_4, %		Fe_3O_4, %		Fe_3O_4, %		Fe_3O_4, %	
Product	Grade	Recovery	Grade	Recovery	Grade	Recovery	Grade	Recovery
Concentrate after five separations	91.5	82.8	92.0	92.2	85.8	66.6	90.7	88.8
Combined middlings	43.3	8.7	32.0	3.3	50.0	11.6	27.5	4.7
Tailing	4.5	8.5	2.5	4.5	11.0	21.8	3.5	6.5
Feed	33.3	100.0	33.7	100.0	33.5	100.0	33.4	100.0

the magnetite stringers progressed in the same direction as the drum, tests 1 and 3, the field frequency should have been 65-70 c.p.s. instead of 31-51 c.p.s. for optimum results.

CONCLUSIONS REGARDING OPTIMUM SEPARATION CONDITIONS

The different factors which affect dry magnetic separation have been examined above. A good concentrate grade is obtained under conditions where the tumbling stringers contain a small number of particles, the number of rearrangements of the stringers in a separation is large, and/or the centrifugal force effecting the discharge of non- magnetic grains is large.

The number of grains in a stringer is decreased if

- the fineness of grinding is coarser
- the field frequency is increased
- the field strength is increased
- the feed rate is decreased.

The number of rearrangements made by the stringers in a separation is increased if

- the field frequency is increased
- the feed rate exceeds a minimum limit, but does not increase to such an extent that the rotations of the stringers are hindered.

The centrifugal force is increased if

- the drum speed is increased
- the field frequency is increased
- the magnet wheel rotates in on opposite direction to the drum.

Again, a good recovery is achieved if the difference between the force of magnetic attraction and centifugal force influencing the magnetic clusters is large. This difference is increased if

- the field strength is increased
- the pole distance is decreased
- the effective permeability of the magnetite stringers is increased
- the centrifugal force is decreased (see above)

In practical application, the aim of a separation process is to produce a concentrate with a high grade and high recovery, using as few separators as possible. By changing the conditions in the successive separations, it as possible to adjust the

grade of concentrate and tailing to the desired quality. According to Figures 23-25 and 27, a minimum number of separators is needed if the conditions are such that the magnetite stringers progress in an opposite direction to the drum, the drum rotates at a speed near the crical value, and the field frequency is about 100 c.p.s. The "scavenger" separator for the tailings must have a drum speed slower than that used in the rougher separation and cleaner stages. The concentrate of the scavenger separator constitutes the circulating load.

A similar end product may be obtained even under other separation conditions, but more separators must be used, because the conditions are not as effective as those described above. If magnetite stringers are progressing in the same direction as the drum, the field frequency should be 65-75 c.p.s. With other field frequencies, the drum speed must be lower and the capacity is decreased.

The nost important types of drum separators with permanent magnets are the Mörtsell-Sala separator[9, 10], the Laurila separator[11] and the Cavanagh separator[12]. The separators differ from each other in the method employed to discharge the concentrate from the drum. In the Mörtsell-Sala separator, the magnet-carrying wheel is stationary, and one section is without magnets. At this section the magnetite flies away from the drum. In the Laurila separator, both the drum and the magnet-carrying wheel rotate concentrically. Magnetite is discharged from the drum surface by means of an induction roller. In the Cavanagh separator, the drum and the magnet carrying wheel rotate eccentrically. Magnetite flies away from the drum surface at that section where the distance between drum and magnet wheel is greatest.

It is apparent on comparison of the separator constructions that the Mörtsell-Sala separator has the simplest design. But the Mörtsell-Sala separator has the disadvantage that the field frequency is not adjustable. Fig. 13 shows that Mörtsell-Sala type separators, with a magnetic attractive force of 6×10^5 N/m^3, pole distance of 52 mm, and drum diameter of 2.0, 1.0, 0.6, and 0.4 m, have at the critical drum speeds, field frequencies of 106, 75, 57, and 46 c.p.s. respectively. This means that if the desired field frequency of 65-75 c.p.s., is to be obtained with a Mörtsell-Sala type separator, the drum diameter must be large. With separators of the Laurila and Cavanagh types, the desired field frequencies can be achieved with moderately-sized drum diameters.

On the other hand, separators of large drum diameter make possible the use of high feed rates. For optimum practical conditions, one should calculate whether it is more profitable to use a few large diameter separators or a number of separators of smaller diameter. The choice between the different types depends on the cost and the reliability in operation.

It might be useful further to investigate the effect of magnetic fields of different strengths and pole distances. The volume of permanet magnet material, which produces a given field strength on the separator drum, is directly proportional to the pole distance[13]. Thus, less permanent magnet material is needed if the pole distance is decreased. A decreasing pole distance also increases the field frequency. On the other hand, a field with a small pole distance does not extend far, and seems to lead to poor separation results. For constructional reasons, the field must extend

some distance, because there should always be a gap between the magnet wheel and the drum, and the shell must have a definite thickness.

Even if the optimum pole distance could be found, it is not likely that development of the present dry separators would greatly improve the separation results. There still remains the harmful effect of gangue dust. This effect should be reduced. Dispersion of the feed suggests itself as an important field for further research.

SUMMARY

The behaviour of magnetite particles in a rotating magnetic field has been investigated by measurement of the velocity of the magnetite clusters, and by photography of their tumbling movement at different field frequencies up to 500 c.p.s.

The results of these investigations proved to be in agreement with the theoretical statements earlier presented by LAURILA

The main factors effective in a dry separation process have been investigated by separation tests with different magnetite ores, and by the employment of two different forms of separator.

The results of separation tests have been theoretically explained, and the optimum conditions for dry separation in a rotating magnetic field discussed.

The construction of dry separators has been analysed in the light of the findings made.

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ERRORS

Page	Line	In place of	Must be
1	4 f.b.	puplic	public
11	9 f.t.	half grains	locked particles
11	10 f.t.	half grains	locked particles
13	15 f.t.	content	contents
14	16 f.b.	polyvinylcloride	polyvinylchloride
15	7 f.b.	f. 8	f: 8
18	5 f.b.	$\mu_a = 1 + 3c + 9c^2 + \ldots\ldots\ldots$,	$\mu_a = 1 + 3c + 3c^2 + \ldots$
19	1 f.t.	$U = -\frac{3}{2} n \frac{1 + 3c}{1 + N(3c + 9c^2 + \ldots)} \mu_o H^2$.	$U = -\frac{3}{2} n \frac{1 + c + c^2 + \ldots}{1 + 3N(c + c^2 + \ldots)} \mu_o H^2$
19	7 f.b.	$F_{c_1} - F_{o_2}$	$F_{c_1} - F_{c_2}$
22	4 f.t.	method.	method:
32	4 f.t.	fims	films.
33	13 f.t.	overisize	oversize
33	3 f.b.	expalains	explains
34	5 f.t.	function 17	function (17)
34	11 f.t.	functions 12, 13 and 14	functions (12), (13) and (14)
35	13 f.t.	carriend	carried
35	4 f.b.	smallerr	smaller
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43	14 f.b. column 180 c.p.s., same direction	1.9 4.[illegible]	1.9 6.1
45	2 f.t.	consitions	conditions
45	24 f.b. column 90 c.p.s., opp. direction	71.7 97.2	71.7 98.2
47	24 f.b. column 50 c.p.s., opp. direction	41.0 94.5	41.0 94.9
47	24 f.b. column 90 c.p.s., opp. direction	41.0 95.3	41.0 95.4
62	16 f.b.	function 10	function (10)
64	1 f.b.	gringing	grinding
66	12 f.t.	followwing condition	following conditions
66	13 f.t.	pecentage	percentage
66	16 f.b.	36 mm	35 mm
66	8 f.b.	grater	greater
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f.t. = from the top
f.b. = from the bottom

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